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OXYGEN CONSUMPTION

IN

CONTINUOUS BIOLOGICAL CULTURE

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16. Abstract

Responses of laboratory scale aeration only and aeration with sludge return completely mixed activated sludge (CMAS) systems to step changes in the influent substrate were determined using a continuous flow automatic recording respirometer. Substrates [redacted] included: glucose; a mixture of glucose, glutamate, and acetate; and a mixture of sewage solids plus Metrecal. Doubling the substrate influent to an aeration only CMAS with a 3 hour detention time produced no changes in effluent soluble COD, and tripling the influent mixture to a similar reactor with a 6 hour mean residence time also produced no measureable variation in effluent soluble COD. Within 3 hours of starting the transients to system 1, and within 5 hours of the introduction to unit 2, the systems were again operating at steady state. A CMAS system with sludge recycle was loaded up to 7.2 times the original loading in step increments with no transient increases in effluent soluble COD. However, the system was not loaded to failure, so no maximum loading was established. A mathematical model was then formulated to predict the oxygen consumption in CMAS systems, both aeration only and aeration with sludge recycle. Comparison of predicted and observed values showed good agreement during the first 6 hours of a transient, after which the assumption that all of the biological solids synthesized remain in the reactor causes the predicted values to be high. (A glossary and bibliography are included.) (Lowry-Texas)

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by

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The University of Kansas
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ABSTRACT

A continuous flow automatically recording respirometer was used to study the response of aeration only and aeration with sludge return completely mixed activated sludge systems to step changes in the influent substrate. The experiments were conducted at 25°C with glucose; a mixture of glucose, glutamate, and acetate; and a mixture of sewage solids plus Metrecal.

Influent substrate concentrations were doubled in the 3-hour and tripled in the 6-hour mean residence time aeration only experiments without increasing the soluble COD in the effluent. Larger shocks produced temporary COD peaks in the effluent. These increases were accompanied by peaks in the oxygen uptake rate in cultures metabolizing the soluble substrates. The mixture of sewage solids and Metrecal did not produce a distinct peak in oxygen demand during transient operation.

Decreases in the influent substrate concentrations produced rapid decreases in the rate of oxygen utilization.

Concentration increases of up to 7.2 in the influent did not produce a change in the effluent soluble COD of aeration with sludge return units. This was not the maximum limit for the process.

A procedure for calculating the rate of oxygen uptake by a CMAS system at any time during a step transient was developed.

This report was submitted in fulfillment of Project Number 17050 DJS, under the partial sponsorship of the Water Quality Office, Environmental Protection Agency.

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SECTION I
CONCLUSIONS

1. The continuous flow respirometer used in this research is an effective instrument for measuring oxygen utilization by biological cultures.

2. Doubling the substrate concentration in the influent will not increase the soluble chemical oxygen demand (COD) in the effluent of an aeration only completely mixed activated sludge system (CMAS) operating on a 3-hour mean residence time at 25°C.

3. A new steady state oxygen utilization rate is established within 3 hours after starting the transients cited in conclusion two.

4. A 3 fold increase in influent substrate concentration will not increase the soluble COD in the effluent of a 6 hour mean residence time aeration only activated sludge system metabolizing soluble substrates. The evidence is inconclusive for systems operating on complex substrates containing colloidal material, but the upper limit appears to be approximately a 2 fold increase.

5. A new steady state oxygen utilization rate is established within 5 hours after starting the transients cited in conclusion four.

6. Step increases in the influent larger than those cited in conclusions 2 and 4 will produce transient peaks of soluble chemical oxygen demand in the reactor effluent. The magnitude of these peaks is proportional to the magnitude of the increase in the influent and the complexity of the substrate.

7. When cultures, grown on simple soluble substrates, are subjected to transients larger than those cited in conclusions 2 and 4, a transient peak in the rate of oxygen utilization will be produced. Cultures grown on complex substrates containing colloidal material will not produce a peak in oxygen demand.

8. Step decreases in the influent of aeration only CMAS systems result in a rapid decrease in the rate of oxygen utilization. A new steady state is usually established within 3 hours.

9. Aeration only CMAS systems having mean residence times

of 6 hours or less can be useful as pretreatment installations. However, most plant scale applications will require the use of a second treatment process to reduce the concentration of soluble COD in the effluent.

10. Completely mixed activated sludge (CMAS) systems with solids recycle can handle large step increases in soluble organic loading without an increase in the soluble COD in the effluent. Step increases of up to 7.2 times did not produce a change in the effluent soluble COD. This was not the maximum limit, however, because the system was not loaded to failure.

11. Loading rate is one of the critical factors in the production of filamentous growth in CMAS systems with solids recycle. Under some conditions loading rates greater than 0.7 pound of COD per day per pound of mixed liquor suspended solids (MLSS) produced filamentous growth. The mean residence time in the aeration basin and the concentration of MLSS were also found to influence the growth of filamentous microorganisms.

12. A method for calculating the oxygen utilization rate for aeration only and aeration with sludge recycle CMAS systems at any time during a step transient was developed.

SECTION II
RECOMMENDATIONS

Additional research should be conducted on the oxygen uptake response of completely mixed activated sludge (CMAS) systems with solids recycle. The objective of this investigation should be the development of a kinetic model which will respond to transient loading conditions.

The technique developed in this research for predicting oxygen utilization of CMAS systems should be evaluated on field scale installations operating under transient conditions.

SECTION III
INTRODUCTION

Historical Review

Since the development of the concept of activated sludge by E. Arden and W. T. Lockett in 1914, the process has undergone numerous modifications. Most of these changes have been introduced in an attempt to improve operational stability. In many instances, the basis for these stability problems has been the rate of oxygen utilization by the biological culture. This is because, in the final analysis, a functionally stable activated sludge installation is one which will maintain an aerobic environment for the microbial population. This does not mean that some modifications of the process are not capable of undergoing temporary periods of anaerobis without experiencing failure. The literature is replete with accounts where plants have continued to operate under periodic oxygen limiting conditions. However, in almost all instances when this occurs, the ability of the process to successfully respond under adverse stresses is compromised. It is therefore important for the designer to avoid anaerobic conditions when possible.

Oxygen limitation in the activated sludge process will occur because of variations in environmental conditions in the aeration basin. The most significant variables are temperature and changes in influent flow rate or concentration of biodegradable organic material. Within the continental United States, the sewage temperature can be expected to vary between 5°C and 35°C. Oxygen limitation normally becomes a critical factor only at higher temperatures. Variations in influent flow rates and nutrient concentrations for a number of widely scattered municipalities have been compiled by Eckhoff and Jenkins (1). Four to five fold variations between the maximum and minimum daily flow were reported. Organic loading, expressed as biochemical oxygen demand (BOD) or suspended solids (SS), showed ten to twenty five fold daily variations. A summary of the findings reported by Loehr (2) on the variation of wastewater characteristics with time is reproduced in Table 1. The hourly changes in BOD loading observed by Tilsworth (3) for the city of Wahoo, Nebraska, 1960, population 3610, are summarized in Table 2. The maximum influent BOD was 480 mg/L while the minimum was 30 mg/L.

The conditions illustrated in Table 1 and Table 2 indicate plant-scale activated sludge plants are continuously subjected to transient or shock loadings.

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Table 1. Variation in Wastewater Characteristics Reported by Loehr (2)

	Monthly (b)	Daily (c)	Hourly (d)
Flow	80 to 120	80 to 110	50 to 140
BOD5 (a)	70 to 120	50 to 150	25 to 220
Suspended solids	80 to 120	50 to 200	25 to 220

(a) Based on mg/l

(b) Percentage of the average month within a year

(c) Percentage of average day within a week

(d) Percent of the average hour within a day

Table 2. Hourly Changes in BOD Loading for Wahoo, Nebraska, Observed on July 7-8, 1966 by Tilsworth (3)

Time	BOD_5 lb/hr	% of Previous Hour	Time	BOD_5 lb/hr	% of Previous Hour
8	23	---	20	43	110
9	51	222	21	36	84
10	73	143	22	27	75
11	82	112	23	22	81
12	74	90	24	19	86
13	63	85	1	18	95
14	68	108	2	12	67
15	64	94	3	7	58
16	52	81	4	4	57
17	55	106	5	3	75
18	50	91	6	5	167
19	39	78	7	10	200
			8	30	300

Scope of Project

As pointed out by Gaudy and Englebrecht (4), three types of transients are possible in activated sludge systems. These are quantitative shifts in the concentration of nutrients in the influent; qualitative loads caused by changes in the chemical composition of the waste; and toxic shock produced by the addition of substances inhibitory to biological growth. Quantitative transients have the greatest potential for producing oxygen stress on a system because the culture is acclimated to the substrate and can react rapidly to increases in the influent nutrient. This research was therefore confined to investigating culture behavior in response to quantitative changes in selected wastes.

The complete mixing modification of the activated sludge process provides maximum hydraulic protection from all types of shock loading because the aeration basin functions as a surge basin to dampen the effect of changes in the influent. This provides operational stability from a microbiological and an oxygen utilization standpoint because conditions change uniformly throughout the aeration basin This research was therefore confined to aeration only and aeration with sludge return,complete mixing activated sludge systems.

The aeration only system was investigated because it offered an opportunity to observe the response of a mixed biological culture to externally imposed changes in growth conditions without the masking effect of recycle sludge.

A second reason for examining the aeration only system is its potential as an advanced waste treatment process. As pointed out by Tenney _et al_ (5)(6), short term aeration followed by chemical flocculation, sedimentation and solids dewatering has potential for simultaneously removing organic carbon, nitrogen, and phosphate. The potential of this approach can be enhanced by the joint use of alum for the chemical precipitation of phosphate and the use of polyelectrolytes for flocculation of microorganisms (6).

The complete mixing, with sludge recycle, modification of the activated sludge process was investigated because it has been demonstrated to be an exceptionally stable and efficient process for use in secondary waste treatment. McKinney _et al_ (7) reported the average five-day BOD removal efficiency for the CMAS plant at Grand Island, Nebraska, to be 94 percent in 1967, 95 percent in 1968, and 98 percent in 1969. Ninety-nine percent removal was attained for 2.5 months of normal operation in 1969 (7).

Previous Investigations

A great quantity of research has been conducted on continuous cultures during the last thirty five years. Numerous mathematical models describing the kinetics of these systems are available in both microbiological and sanitary engineering publications. Excellent reviews of this literature have been compiled by Agnew (8) and Chun (9). Therefore only a brief review of the concepts of models pertinent to this report will be presented herein. A comprehensive bibliography on continuous culture is presented in Appendix A.

The early work in continuous culture was done by microbiologists who were primarily interested in aeration only steady state systems. The classical kinetic model used to describe these systems was developed by Monod (10), and by Novick and Szilard (11). The model is based upon two basic postulates:

A. The cell yield factor is constant
B. The specific growth rate for a culture can be defined by a single continuous function

The yield factor (Y) is defined by:

$$(1)\quad Y = \frac{\text{dry weight of cells formed}}{\text{weight of substrate utilized}}$$

Considerable controversy has been generated over this postulate. Herbert et al (12) reported a varying yield factor when the dilution rate was increased. Rickard and Gaudy (13) observed decreasing cell yield with increasing liquid turbulence. Hetling et al (14) demonstrated cell yield varied with substrate, organism, and detention time. Gaudy and Gaudy (15) in reviewing the literature, reported cell yield was not constant.

Much of the confusion regarding cell yield can be explained by considering the growth state of the culture. The amount of biological protoplasm observed in a culture is the net result of two opposing processes, synthesis and endogenous metabolism. When food is not limiting, the relatively rapid synthesis reaction predominates producing exponential growth conditions and the yield factor appears to be constant. However, under food limitation, declining growth is observed and a balance is established between the rate of synthesis and the rate of endogenous respiration. Under these conditions the apparent yield factor is determined by the growth conditions externally imposed on the culture. In the activated sludge process, hydraulic detention and sludge recycle are used to operate the system. The yield factor observed in a particular installation is therefore a function of these two process variables.

The specific growth rate (Θ) was defined by Monod (10) as:

$$(2)\quad \Theta = \Theta_{max}\left(\frac{S}{K_s+S}\right)$$

where Θ_{max} = maximum specific growth rate

S = substrate concentration in the reactor

K_s = substrate concentration when the specific growth rate is one half the maximum specific growth rate

The specific growth rate equation is an empirical relationship which best described, for Monod, the growth rate observed in batch systems. Modifications to the relationship have been proposed by Teissier (16), Schulze (17), and Contois (18). However, the Monod equation has remained dominant in the field because it is relatively simple, and because it permits the calculation of specific growth rate throughout the entire range of externally imposed growth conditions. This latter feature is especially appealing from the standpoint of mathematical model development.

Pert (19) was one of the few microbiologists to investigate the effects of dissolved oxygen concentration on continuous cultures. He studied the metabolism of glucose by an Aerobacter species and developed the following relationship for steady state oxygen utilization.

$$(3)\quad \frac{dO}{dt} = - PDS_o$$

where $\frac{dO}{dt}$ = oxygen utilization rate

P = oxygen demand constant

D = reactor dilution rate

S_o = influent substrate concentration

The oxygen demand constant (P) is determined by simultaneously measuring the rate of substrate and oxygen utilization for the culture being studied. The equation is based upon the Monod concepts for continuous culture.

Garrett and Sawyer (20) first evaluated the use of Monod's equations for completely mixed activated sludge (CMAS) systems. They recommended the specific growth rate equation be expressed as two discontinuous functions one for biological mass limiting,and one for food limiting conditions. Because of solids recycle, activated sludge systems were found to be food limited. Under food limiting conditions the growth rate was found to be directly proportional to the soluble BOD remaining in solution. Similar results were reported by Hoover and Porges (21)(22) from continuous flow studies on the treatment of milk wastes.

In 1962, McKinney (23) presented a series of mathematical relationships for completely mixed activated sludge systems. The equations were developed for systems operating predominately in declining growth under food limiting conditions and considered the effect of endogenous respiration as a separate constituent in the kinetic balance of the system. The concepts of Garrett and Sawyer (20) were used to define growth rate. As originally developed,the equations contained ten constants to describe three variations of the basic CMAS treatment process. The modifications considered were: aeration only, aeration plus sludge return with sludge wasting in the effluent, and aeration plus sludge return with separate sludge wasting.

In 1969, McKinney (24) condensed the equations originally proposed for the three process modifications into one set of generalized relationships. These new equations assumed that bacterial activitiy in the final clarifier did not continue in direct progression from the aeration tank, as was assumed in the earlier paper. Only three constants were required. The modified McKinney equations are used later in this report and are therefore described below.

The flow diagram for an aeration plus sludge return system with separate sludge wasting is given in Figure 1. A materials balance around the aeration basin results in the following rate equations for food.

$$(4)\ VdF/dt = QF_i - VK_mF - (Q+Q_r)F + Q_rF$$

where V = volume of aeration basin (L)

$\frac{dF}{dt}$ = food utilization rate (mg/L/hr)

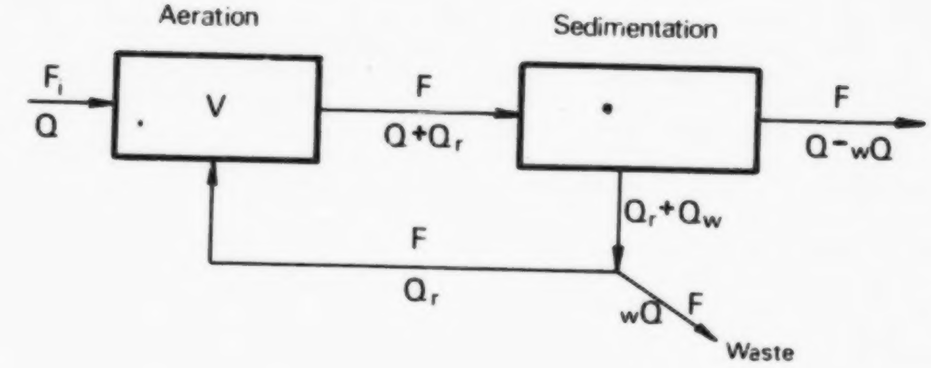
Aeration
Sedimentation
F_i
Q
V
F
Q+Q_r
F
Q-wQ
Q_r+Q_w
F
Q_r
wQ
F
Waste

Figure 1. Flow diagram for completely mixed activated sludge system showing food and discharge distribution.

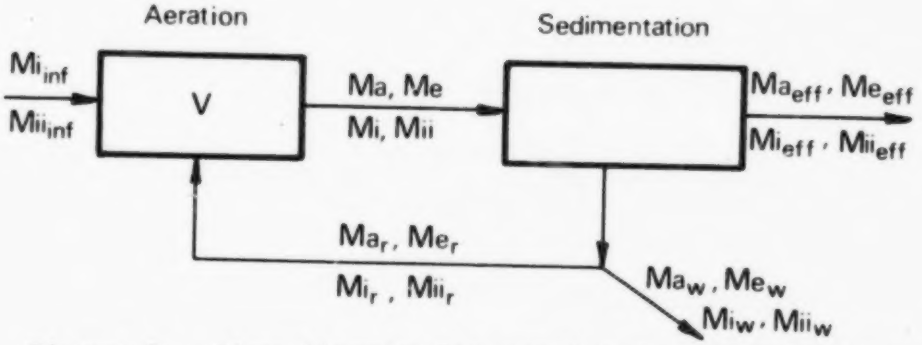
Aeration
Sedimentation
Mi_inf
Mii_inf
V
Ma, Me
Mi, Mii
Ma_eff, Me_eff
Mi_eff, Mii_eff
Ma_r, Me_r
Mi_r, Mii_r
Ma_w, Me_w
Mi_w, Mii_w

Figure 2. Flow diagram for completely mixed activated sludge system showing suspended solids distribution.

Q = rate of flow for the raw waste (L/hr)

F_i = concentration of BOD_5 in raw waste (mg/L)

K_m = metabolism constant (temperature dependent)

F = concentration of BOD_5 in the effluent (mg/L)

Q_r = rate of flow for the return sludge (L/hr)

The first term on the right-hand side of the equation represents the increase due to influent food, the second term represents a decrease in the food due to biological metabolism, the third term represents the decrease due to hydraulic displacement, and the fourth term represents the increase in food due to the return sludge.

At steady state dF/dt = 0, and the equation becomes

$$(5) \quad F = \frac{F_i}{K_m t+1}$$

where $t = \frac{V}{Q}$ = the aeration time based on raw waste flow (hr)

A similar materials balance for microbial mass around the aeration basin gives:

$$(6) \quad VdM_a/dt = Q_r Ma_r + VK_s F - VK_e Ma - (Q+Q_r)Ma$$

where dMa/dt = rate of change in active mass (mg/L/hr)

Ma = active microbial mass (mg/L)

Ma_r = active microbial mass in the return sludge (mg/L)

K_s = synthesis constant (temperature dependent)

K_e = endogenous respiration constant (temperature dependent)

The first term on the right-hand side of the equation represents the increase in active mass due to sludge return, the second term represents the increase due to cell growth, the third term represents the decrease due to endogenous respiration, and the fourth term represents the decrease due to hydraulic displacement.

The active mass in the return sludge (M_{ar}) can be expressed as a fraction (x) of the total active mass (Ma). The rate of flow for the return sludge (Q_r) can also be expressed as a fraction (y) of the influent flow rate (Q). Making these substitutions and assuming steady state conditions so dMa/dt = 0 produces:

$$(7) \quad M_a = \frac{K_s F}{\frac{1+y+xy}{t} + K_e}$$

McKinney indicates the term $\frac{1+y+xy}{t}$ is approximately equal to $1/t_s$ where t_s is the sludge turnover time. Thus equation 7 becomes:

$$(8) \quad M_a = \frac{K_s F}{\frac{1}{t_s} + K_e}$$

where t_s = sludge turnover time (hr)

= lbs MLSS in aeration tank/(lbs SS in effluent per day + lbs SS wasted per day ± lbs SS change in mixed liquor per day)

SS = suspended solids

MLSS = mixed liquor suspended solids

It is worthwhile to note in the McKinney approach the components which make up the total mixed liquor suspended solids. These are illustrated in Figure 2 where:

$M_{I_{inf}}$ = inert, non-biodegradable organic solids in influent (mg/L VSS)

$M_{II_{inf}}$ = inert, inorganic suspended solids in influent, ash fraction of influent suspended solids (mg/L SS)

M_I = inert, non-biodegradable organic suspended solids in the aeration tank (mg/L VSS)

M_{II} = inert, inorganic suspended solids in the aeration tank (mg/L SS)

M_e = endogenous respiration mass

The last three components can be calculated by the following equations:

$$(9)\ M_I = M_{I_{inf}}\ (t_s/t)$$

$$(10)\ M_{II} = M_{II_{inf}}\ (t_s/t) + 0.1(M_a + M_e)$$

$$(11)\ M_e = 0.2\ K_e M_a t_s$$

The last term in equation 10 accounts for the inorganic components present in the non-biodegradable protoplasm synthesized by the microbial culture. The constant 0.2 included in equation 11 is the fraction of protoplasm synthesized by the culture which is not biodegradable. The total mass of the mixed liquor suspended solids in the aeration tank is therefore:

$$(12)\ M_T = Ma + Me + M_i + M_{ii}$$

The solids accounting system given by equation 12 illustrates the difference between active mass (Ma) and the total mixed liquor volatile suspended solids (MLVSS) which include ($Ma+Me+M_i$). The active mass (Ma) in an aeration only system operating in exponential growth is closely approximated by the mixed liquor volatile suspended solids (MLVSS), but this approximation begins to deteriorate when the culture shifts into declining growth. The approximation becomes grossly in error with the introduction of solids recycle because of the buildup of endogenous mass and inert organic material. This is illustrated in Figure 3 for an average municipal waste being treated at 20°C in a plant with a 3 hour aeration time.

A materials balance around the aeration basin also permits development of an equation for predicting the oxygen utilization rate in the basin. The dissolved oxygen in the liquid entering and leaving the basin is neglected in this derivation because the net effect of these components is negligible. On this basis, the oxygen utilization rate equation for the aeration basin is:

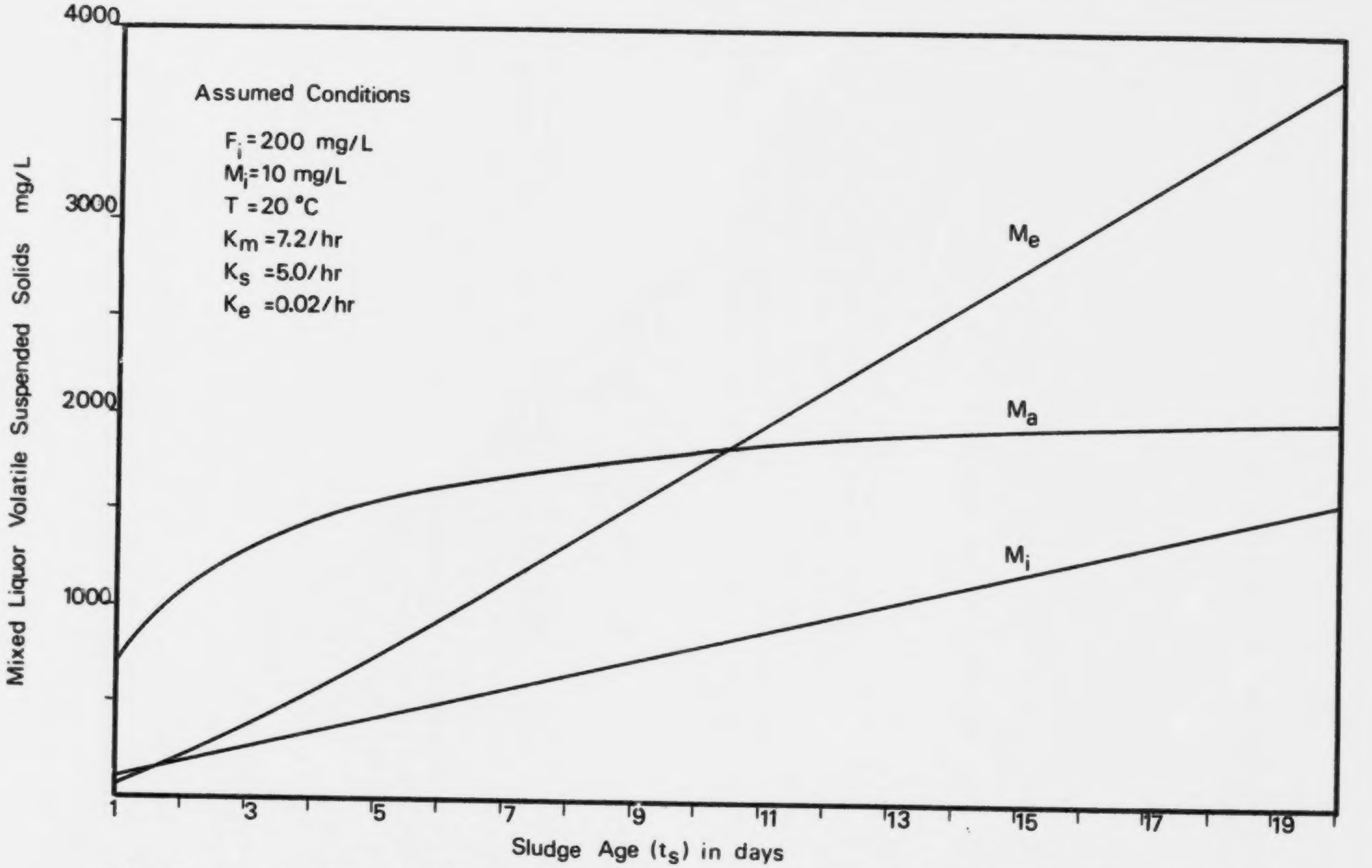

Figure 3. Change in the components of the mixed liquor volatile suspended solids in the aeration basin of a completely mixed activated sludge plant as the sludge age is varied.

$$(13)\quad dO/dt = \frac{1.5(F_i - F)}{t} - \frac{1.42(Ma+Me)}{t_s}$$

where dO/dt - oxygen utilization rate mg/L/hr)

The constant 1.5 in equation 13 converts the five-day BOD measurements to ultimate BOD. The constant 1.42 converts the biologically active solids measurements to oxygen equivalents. The oxygen equivalent of these solids are subtracted from the overall oxygen utilization rate equation because this material is the net loss in microbial respiration from the aeration basin due to sludge wasting. Both constants in equation 13 are based on the metabolism of domestic wastes. Their values will change for activated sludge grown on substrates which vary appreciably in chemical composition from domestic wastes.

The five day effluent BOD from the system is given by:

$$(14)\quad \text{Eff. } BOD_5 = F + F_B M_{a(eff)}$$

where Eff. BOD_5 = the five-day BOD of the effluent (mg/L)

K_B = BOD_5 factor for converting active mass to oxygen equivalent (not temperature dependent because the BOD5 test is performed at 20°C)

The key to successful application of McKinney's equations lies in the values used for the constants. The 20°C values recommended for the metabolism factor (K_m) is 7.2/hr, while the synthesis factor (K_s) is 5.0/hr, and the endogenous factor (K_e) is 0.02/hr (24). The variation in these constants with temperature is summarized in Table 3.

The value of the effluent BOD constant (K_B) is 0.8 which agrees with the experimental results of McCarty and Broderson (25) as well as with theoretical relationships.

With few exceptions, transient model development has been based upon modifications of the basic Monod postulates for cell yield and specific growth rate. Use of the Monod concepts has been essentially universal when considering

Table 3 - Temperature Effect on the Metabolism, Synthesis, and Endogenous Respiration Factors Reported by McKinney (24)

Temperature °C	Multiplication Factor	Temperature °C	Multiplication Factor
4	0.34	22	1.15
6	0.38	24	1.32
8	0.44	26	1.50
10	0.50	28	1.75
12	0.58	30	2.00
14	0.66	32	2.30
16	0.76	34	2.65
18	0.87	36	3.10
20	1.00	38	—*

*Destruction of the culture starts to occur

transient response to quantitative shock loading. The work of Storer and Gaudy (26) indicates this approach breaks down during large transients and a growth rate hystersis, similar to that proposed by Perret (27) on theoretical grounds, occurs.

A more fruitful approach to transient model development would appear to be based on the concept of a definite synthesis, not yield, relationship as proposed by McKinney (24), and by Burkhead and McKinney(28) and; on the postulate that specific growth rate is limited either by the active mass or the concentration of food available in the aeration basin as originally proposed by Garrett and Sawyer (20). The key to use of this type of model is determining the food to active mass ratio which controls the specific growth rate of the system.

Objective of the Project

The objectives of this research were to measure changes in the rates of oxygen utilization by activated sludge cultures operated under transient loading conditions and to develop from these measurements a set of design criteria useful for sizing oxygen supply systems for field installations.

Development of new mathematical models for continuous culture systems operating under transient growth conditions was not undertaken.

SECTION IV
EQUIPMENT DESIGN

Basic Concept

A respirometer capable of measuring the oxygen utilization of a continuous culture was used in this research. Schematic diagrams of two modifications of the apparatus are given in Figure 4 and Figure 5. The basic principles of both systems are identical. The difference between the units being that one operates as an aeration only system while the second incorporates secondary sedimentation, sludge wasting, and sludge return. In both systems, the reactor, or aeration basin, operates as an externally controlled, constant temperature, completely mixed vessel. Nutrient is introduced into the reactor with a constant flow pump. The volume of liquid in the vessel is held constant by an overflow tube.

The air space above the liquid in the reactor is sealed from the outside atmosphere. Gaseous carbon dioxide produced by the culture is removed by reaction with potassium hydroxide. A barometric switch is used to activate the power supplies used to replenish the oxygen consumed by the culture. The oxygen is produced by the direct-current electrolysis of water. The quantity of oxygen produced is measured by recording the length of time the electrolysis cells operate over any specified interval.

The concentration of dissolved oxygen in the influent and within the reactor is continuously measured and recorded by polarographic electrodes.

The net rate of oxygen utilization by the culture is obtained by computing the oxygen mass balance of the system over a specific time interval. This computation takes the form:

$$(15)\quad O_2\ (\text{net}) = (DO_{in})(V) - (DO_{out})(V) + O_2(E) \pm B$$

where O_2 (net) = oxygen used by the culture (mg/min)

DO_{in} = concentration of dissolved oxygen in influent (mg/liter)

DO_{out} = concentration of dissolved oxygen in reactor (mg/liter)

$O_2(E)$ = oxygen supplied by electrolysis

V = liquid volume pumped through reactor (L/min)

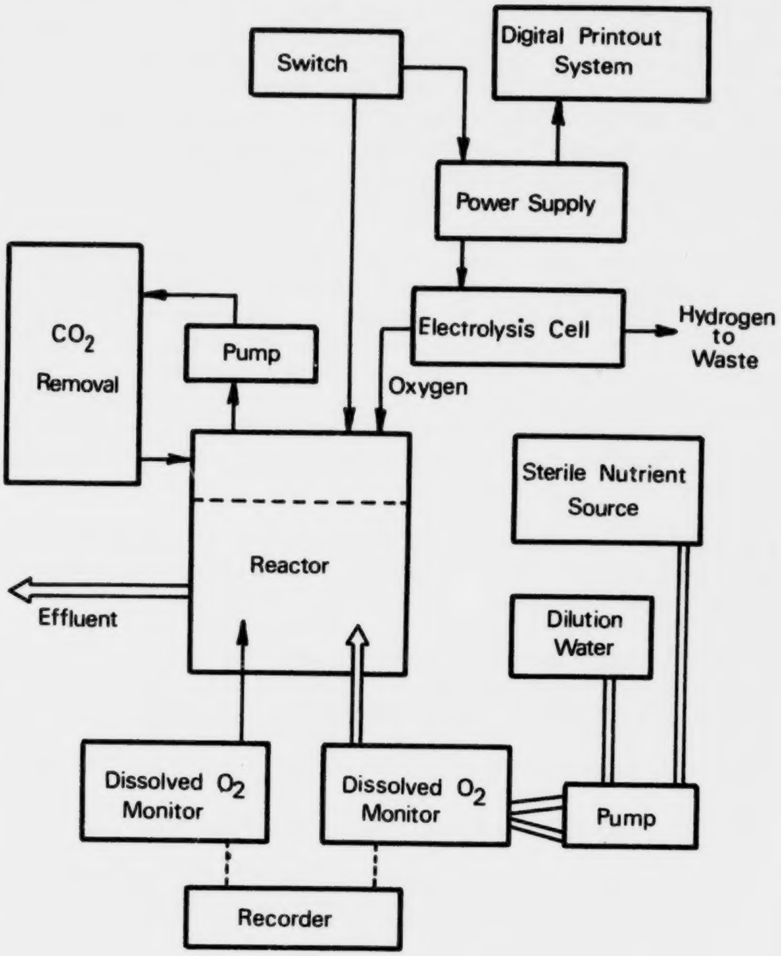
Switch
Digital Printout System
Power Supply
CO₂ Removal
Pump
Electrolysis Cell
Hydrogen to Waste
Oxygen
Reactor
Sterile Nutrient Source
Effluent
Dilution Water
Dissolved O₂ Monitor
Dissolved O₂ Monitor
Pump
Recorder

Figure 4. Schematic diagram of respirometer used for aeration only experiments.

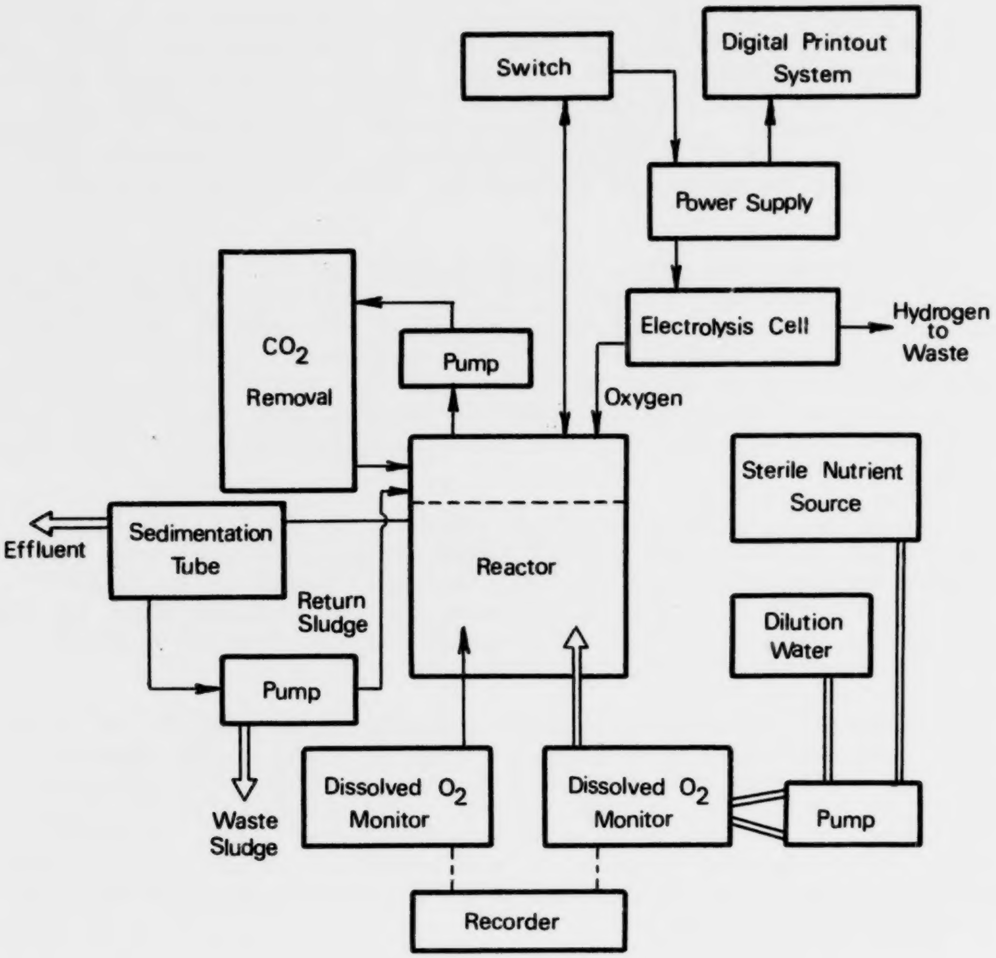
Switch
Digital Printout System
Power Supply
Electrolysis Cell
Hydrogen to Waste
Oxygen
CO_2 Removal
Pump
Reactor
Sterile Nutrient Source
Sedimentation Tube
Effluent
Return Sludge
Dilution Water
Pump
Waste Sludge
Dissolved O_2 Monitor
Dissolved O_2 Monitor
Pump
Recorder

Figure 5. Schematic diagram of respirometer used for aeration with sludge return experiments.

B = correction for change in barometric pressure (mg/min)

Equipment Details

An adjustable stroke piston pump was used to transfer liquid into the reactor. A number of laboratory pumps satisfactory for this application are commercially available. In some instances, it was also expedient to separate the liquid being pumped into the reactor into two components to facilitate sterilization of the nutrient. When this was done, the water used to dilute the nutrient contained the trace minerals, nitrogen and phosphorous necessary for balanced biological growth. Constant head valves were generally required between the liquid storage reservoirs and the suction line of the pump to maintain a constant rate of flow into the reactor.

A staisfactory reaction vessel can be constructed by modifying almost any of the commercially available laboratory fermentors. The basic requirements are: the vessel should be air tight; the temperature within the reactor should be maintained within plus or minus 0.25°C; and the intensity of agitation in the liquid should be sufficient to provide complete mixing and adequate mechanical aeration of the culture.

Aeration using either surface paddles or draft tubes has been used successfully. Diffused aeration, using the atmosphere enclosed by the system, was not found to be satisfactory because slight variations in the pumping rate of the gas produced significant errors in the barometric switch used to control the oxygen supply.

The effluent from the reactor overflowed through a "U" tube to a sampling port and then to a waste sump. The bottom of this tube was mixed with a magnetic stirrer to prevent settling of the biological solids. It is relatively simple to design an overflow tube which maintains equal concentrations of suspended solids in the reaction vessel and in the effluent when the biological solids are either discrete or flocculent particles.

The gaseous carbon dioxide produced by the culture was removed by recirculating the gas in the reactor through a series of two scrubbers each containing 700 milliliters of 10 Normal potassium hydroxide solution. A diaphram pump was satisfactory for this purpose. A water trap was installed between the final gas scrubber and the reactor to prevent the caustic solution from being carried into the reactor.

The gas adsorption train was installed in a water bath which was maintained at the temperature of the reactor to prevent thermally induced volume change in the recirculated gas.

The concentration of dissolved oxygen in the influent and in the reactor was continuously measured with polarographic electrodes which were separated from the liquid by a gas permeable membrane. A multi-channel recorder provided a permanent record of these observations.

Most commercially available dissolved oxygen electrodes require a minimum liquid velocity past the membrane of approximately 1.8 feet per second. This velocity was easily attained in the reactor but could not be obtained in the influent line unless a small mixing chamber was provided. A satisfactory chamber was constructed by mounting a small cylindrical container on a magnetic stirrer. The measuring probe was inserted through the top of the cylinder directly above the stirring bar.

The electrodes measure the dissolved oxygen tension in the liquid. These measurements can be converted to dissolved oxygen concentration by calibrating the electrodes in a solution of the culture media. The "Short Theriault Modification" of the Winkler method (29) was found satisfactory for this purpose.

The oxygen used by the biological culture was supplied by the electrolysis of water, Milazzo (30). A group of power supplies, each attached to an individual electrolysis cell, was used to provide discrete increments of gas production until the rate of oxygen demand by the culture was satisfied. Operation of the power supplies was controlled by a null point manometric switch. When oxygen was consumed by the culture, the pressure dropped in the reactor and lowered the electrolyte level in the atmospheric arm of the manometer. This broke electrical contact across the switch and turned on power supplies sequentially until sufficient oxygen was being produced to restore the original atmospheric pressure in the reactor. In practice this meant that one or more electrolysis cells operated continuously with intermittent operation from an additional unit.

A number of direct-current power supplies satisfactory for this application are commercially available. The basic requirements are: the power supply should provide a constant direct-current with variable voltage; the output of the power supply should be regulated within plus or minus 0.5 milliamperes; and the circuitry of the power supply should be solid state to minimize response time when the unit is turned on.

The use of a manometric switch to control the operation of the power supplies necessitated the use of a correction factor to compensate for changes in atmospheric pressure during an experiment. This correction was readily computed once the temperature of the experiment was selected and the average volume of the gas enclosed in the respirometer was measured. A standard commercial recording barograph provided a permanent record of atmospheric pressure change which was of satisfactory accuracy for computing this correction.

The electrolysis cells used in the apparatus are shown in Figure 6. Each ampere-hour of current flow through the cell produced 0.037 grams of hydrogen gas at the cathode and 0.298 grams of oxygen gas at the anode. The anode consisted of 20 feet of 0.7 millimeter diameter nickel wire wrapped around a 4 millimeter diameter glass rod 8.5 inches long. This rod was enclosed within a plastic drying tube which had been slotted lengthwise throughout its circumference. The outside of the drying tube was wrapped with 20 feet of one millimeter iron cathode wire. The entire assembly was suspended in a large test tube filled with an electrolyte of 7.6 Normal potassium hydroxide solution. The oxygen gas produced at the anode was connected to the reactor. The hydrogen gas produced at the cathode was vented to the atmosphere.

Cells of the type shown in Figure 6 were operated at currents up to 2 amperes for periods of up to 2 years without discernable physical deterioration or current drift. A potential of approximately 3.5 volts was required across the cell.

Current efficiency is defined as the observed weight of oxygen produced by an electrolysis cell divided by the theoretical weight of oxygen which should have been produced in accordance with Faraday's law. The current efficiency of the cells shown in Figure 6 was measured by collecting the oxygen produced during a 15 minute time period in a burette filled with a saturated sodium chloride solution. The range in current efficiency observed during five trials was from 99.2 to 100 percent. The average of all observations was 99.7 percent.

The composition of the gas collected at the anode was also measured with a gas chromatograph. Less than 0.01 percent hydrogen gas contamination was observed.

The period of operation of each power supply was recorded with a digital accumulator and printout system designed by A.R.F. Products of Raton, New Mexico. A block diagram showing the major components of this system is shown in Figure 7. The time of day clock has a visual dial and is also directly connected to the printer. The minimum time increment is

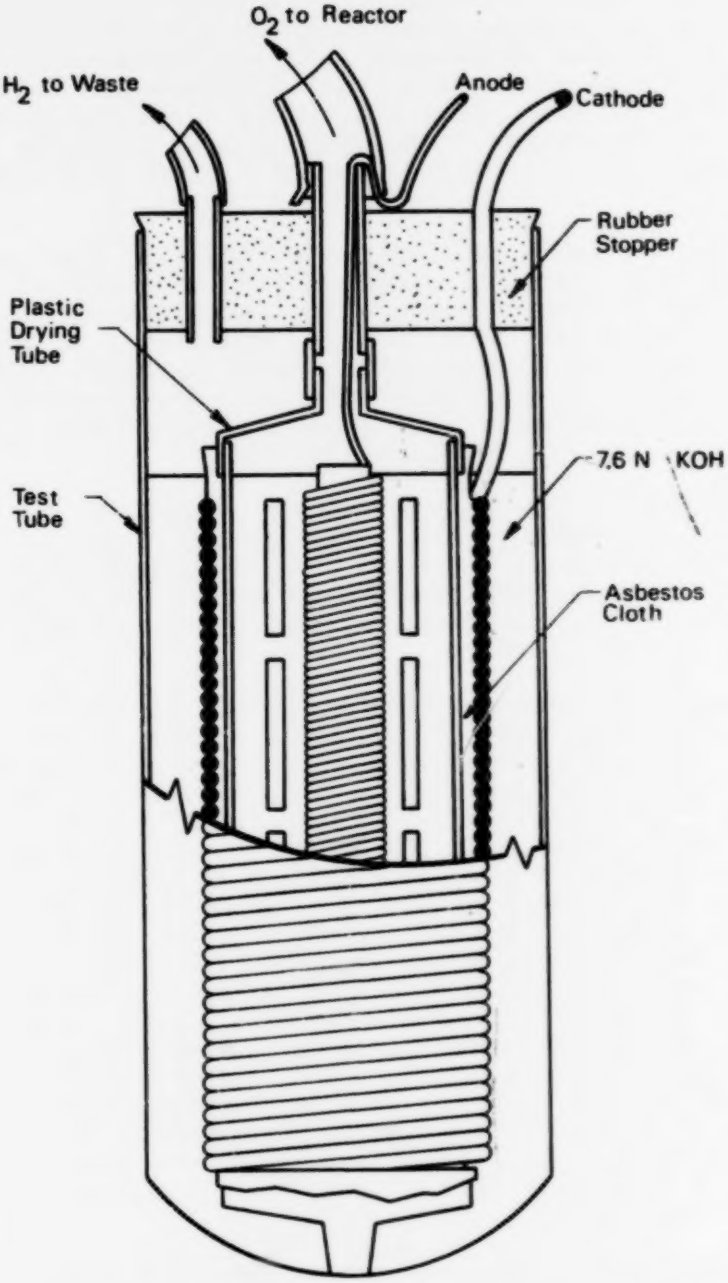
O_2 to Reactor
H_2 to Waste
Anode
Cathode
Rubber Stopper
Plastic Drying Tube
7.6 N KOH
Test Tube
Asbestos Cloth

Figure 6. Electrolysis Cell Designed for Use With the Respirometer

hundredths of hours. The elapsed time accumulator visually displays, and sends to the printer on demand, the total time each power supply operates within a specified time interval. However, rather than simply recording the time of operation, the unit is calibrated to provide a direct tabulation of the milligrams of oxygen produced by each electrolysis cell. The accumulator can also clear the values displayed for any power supply in the system. This may be done manually or may be done automatically at the end of a specified time interval.

The multiplexer consists of a variable timer and the circuitry necessary to transfer readings from the elapsed time accumulator to the printer. Time intervals of from one to sixty minutes can be selected. However, a 15 minute interval was found to provide sufficiently detailed information for the majority of experiments. A more complete description of the accumulator, multiplexer, and digital printout system has been provided by Baker (31).

The digital printer provides a permanent record of the oxygen produced by electrolysis. This record together with the record of the concentration of dissolved oxygen entering and leaving the reactor and the record of the change in barometric pressure provided all of the data necessary to make an oxygen mass balance.

A check on the accumulative accuracy for all of the components connected with the oxygen supply system of the respirometer was made by comparing the observed versus the theoretical oxygen consumption of a standardized solution of sodium sulfite. Four trials were conducted. In the first 3 the volume of the liquid in the reactor was 5.19 liters. In trial 4 the volume of the liquid was 9.25 liters. In all trials the sodium sulfite and the cobaltous chloride solutions were prepared separately and combined in the reactor. This was accomplished in trials 1 and 2 by adding cobaltous chloride to the distilled water in the reactor to make solutions of 157 mg/L and 552 mg/L as cobalt respectively. These initial concentrations were based upon maintaining a catalyst concentration in the reactor greater than 10 percent of the incoming sulfite concentration during the 6 hours over which the tests were conducted. In trials 3 and 4 the chemical solutions were pumped into the reactor which initially contained distilled water. A summary of the operating variables is given in Table 4.

Sulfite was measured by the non-referee method C given in the ASTM Manual on Industrial Water and Industrial Waste Water (32). A nitrogen atmosphere was maintained over the sulfite solution during standardization and storage. Dissolved oxygen was measured with a polarographic membrane

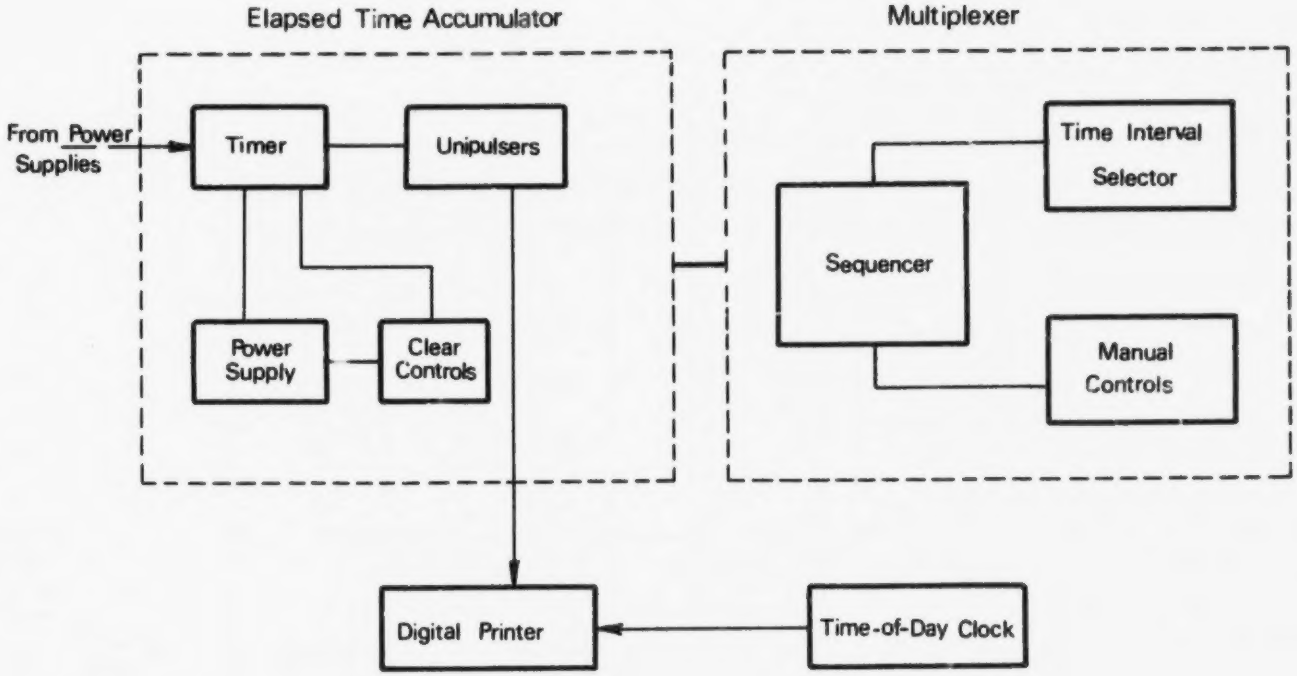
Elapsed Time Accumulator
Multiplexer
From Power Supplies
Timer
Unipulsers
Power Supply
Clear Controls
Sequencer
Time Interval Selector
Manual Controls
Digital Printer
Time-of-Day Clock

Figure 7. Schematic diagram of digital accumulator and print-out system used with the respirometer.

Table 4 - Pumping Rates and Chemical Concentrations Used in Respirometer Oxygen Calibration Tests

Trial	Pumping Rate L/hr		Influent Concentration mg/L	
	Sulfite	Cobalt	Sulfite	Cobalt
1	1.73	0	208	*
2	1.73	0	725	*
3	1.75	0.89	1390	140
4	2.65	0.40	1500	160

*batch addition, see explanation in text electrode calibrated against the Axide Modification of the Iodometric Method (29).

The results of the test are summarized in Table 5.

The values shown in Table 5 are of interest in that they illustrate the precision of the apparatus while also showing how sulfite measurements can be used as an independent check on the performance of individual components in the system. This is illustrated in trials 1 through 3 which were conducted under identical environmental conditions with the only variable being the concentration of the influent sulfite solution. The consistently indicated overproduction of oxygen by the respirometer and the relative decrease in overproduction as the concentration of the sulfite solution increased, strongly implies one of the power supplies providing the base-line oxygen supply was incorrectly adjusted and was not providing sufficient current to the elctrolysis cell to produce the oxygen indicated on the time accumulator. This resulted in the power supply, which responded to the small intermittent pressure drops in the reactor, operating more often and produced an over-estimate for oxygen utilization. While the absolute magnitude of this error was constant, the net effect was less pronounced as the concentration of sulfite was increased and additional power supplies were used to produce the required oxygen. Unfortunately, trial 4 can not be included in this hypothesis because a larger reactor was used and supplemental power supplies were required to provide the rate of oxygen production needed to oxidize the sulfite solution.

Solids separation was obtained by a tube settler designed for a 2-hour liquid retention time. Sludge recycle was done with an adjustable flow piston pump connected to the bottom hopper of the tube settler. Sludge wasting was not done from the sludge return line because a constant sludge concentration could not be maintained. Accurate control of the mixed liquor suspended solids (MLSS) was obtained by wasting mixed liquor collected from the effluent of the aeration basin.

A summary of the equipment used in constructing the respirometers is given in Table 6. The identification of specific manufacturers in Table 6 is for illustration only and does not constitute the endorsement of the products mentioned.

Table 5 - Results Obtained in Calibrating the Respirometer Against Standard Sodium Sulfite Solutions

Trial No.	Sulfite Oxygen Demand Entering Reactor mg/hr	Dissolved Oxygen Leaving Reactor mg/hr	Total Oxygen Production Required mg/hr	Oxygen Production Indicated on Respirometer Printout mg/hr	Percentage Difference
1	72	4	76	81	107
2	250	1	251	264	105
3	487	8	495	497	100
4	795	28	823	843	102

Table 6 - Components Used to Construct the Respirometers Used in This Research

Components	Manufacture
Nutrient and Dilution Water Pump	Model 1521 Harvard Metering Pump
Dissolved Oxygen Analyzer	Model 778 Beckman Process Oxygen Analyzer
Recorder for Dissolved Oxygen Measurements	Electronik 16 Honeywell Multi-Channel Recorder
Reactor 7.5 Liter Capacity	Microfirm Fermentor Series MF-100, New Brunswick Scientific Company
Reactor 12 Liter Capacity	Model 40-100 Fermentor, The Virtis Company
Constant Current Power Supplies	Models ABC15, ABC18, and CK18, Kepco, Inc.
Digital Accumulator and Printout System	A.R.F. Industries, Raton, New Mexico
Atmospheric Recirculation Pump	Model 2 Neptune Dyna-Pump
Sludge Recirculation Pump	Model RRP2G150, FMI Lab Pump

SECTION V
EXPERIMENTAL PROCEDURES

Substrate Selection and Preparation

The problem of choosing substrates which can be prepared and standardized in the laboratory, yet at the same time yield information useful for field application, is one which has plagued activated sludge research for decades. The compounds used in this research were selected with the objective of determining differences in the response of cultures grown on simple carbon substrates with those grown on complex mixtures of carbon compounds.

Glucose was selected as the single carbon source for one series of the aeration only experiments because of the large number of investigations available in the literature which are based on this compound. A second waste used in the aeration only experiments was composed of a mixture of glucose, glutamic acid, and acetic acid. This waste had been studied by Burkhead (33) and was considered to be representative of the soluble portion of domestic sewage. The third waste used in this series was a mixture of the supernatant from settled primary sewage sludge and a diet food, Metrecal. A summary of the percent total oxygen demand (TOD) of the various waste components is given in Table 7.

During the aeration only experiments, the glucose and the carbon compounds used in the composite waste were prepared as concentrated solution, and acidified to a pH between 2.0 and 3.0. Iron, as ferrous sulfate, was added and the mixture autoclaved at 15 psig for 15 minutes. These sterile solutions were pumped separately to the reactor.

The separation of the carbon substrate from the remainder of the waste resulted in a stable nutrient source throughout the course of the experiment. One additional benefit which resulted from this approach was that iron could be readily held in solution in the acidified substrate. Previous researchers (34)(35) had reported the precipitation of iron and other trace metals when substrate, nutrients, and trace metals were combined. No precipitation was observed in the carbon substarte containers in this research. Occasional measurements of soluble iron in the reactor effluent during the experiments indicated a minimum of 0.4 mg/L of iron present.

The supplemented sewage used in the aeration only experiments was prepared by collecting approximately 10 liters of primary sewage sludge from the sewage treatment plant at Lawrence, Kansas. The sludge was homogenized in a Waring Blender by mixing in the proportion of about 1 part sludge to 3 parts of tap water. This material was then refrigerated for 24

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Table 7 - Percent Total Oxygen Demand Contribution of the Various Waste Components used in the Aeration Only Activated Sludge Experiments

Waste Name	Carbon Compounds	% TOD Contribution
Glucose	Glucose	100
Composite	Glucose	40
	Glutamic Acid	50
	Acetic Acid	10
Synthetic Sewage	Supernatant from Settled Primary Sewage Sludge	19*
	Metrecal	81*

* Percentages based on Chemical Oxygen Demand (COD) rather than TOD

Table 9 - Nutrient Concentrations in the Influent Waste Use in the Aeration Plus Sludge Return Activated Sludge Experiments

Aeration Time Hours	TOD of Waste mg/L	Nitrogen mg/L as N	Phosphorous mg/L as P	Iron mg/L as Fe	Buffer mg/L as HCO_3
3	250	33.7	3.0	4	87.1
3	500	67.3	6.1	4	87.1
3	750	101.0	10.1	4	87.1
3	1000	134.7	13.1	4	87.1
6	250	42.8	3.9	4	112.4
6	500	85.6	7.7	4	112.4
6	750	128.4	11.6	4	112.4
6	1000	173.2	15.4	4	112.4

hours at 5°C. The supernatant was decanted off, thoroughly mixed, and divided into two 20 liter containers. The solution in each container was then supplemented with 570 milliliters of Metrecal to produce a total concentration of 10.7 grams/liter as chemical oxygen demand (COD). These stock solutions were refrigerated at 5°C until used.

The water used to dilute the influent carbon solutions of all three wastes was prepared from Lawrence, Kansas, tapwater to which nitrogen, as ammonium chloride; phosphorous, as potassium acid phosphate; and buffer, as sodium bicarbonate; had been added. A summary of the nutrient concentrations for each influent waste is given in Table 8. It should be noted that iron was not added to the synthetic sewage mixture because it was present in the Metrecal.

The only waste used in the aeration with sludge return experiments was the mixture of 40 percent glucose, 50 percent glutamic acid, and 10 percent acetic acid used as one of the carbon sources in the aeration only experiments. In this instance, however, the mixture was not acidified. Iron was maintained in solution at 4 mg/L as iron by chelation with sodium citrate using a citrate to iron weight ratio of ten to one. The stock solutions were sterilized by autoclaving and pumped separately to the reactor.

The water used to dilute the influent carbon solution was prepared from Lawrence, Kansas, tapwater to which nitrogen, as ammonium sulfate; phosphorous as dibasic potassium phosphate; and buffer, as sodium bicarbonate; had been added. A summary of the nutrient concentrations used for each experimental condition is given in Table 9. The dilution water and the influent carbon source were changed simultaneously at the start of a transition.

Analytical Techniques

The analytical tests used to supplement the oxygen utilization measurements collected in this research were: total suspended solids; chemical oxygen demand; biochemical oxygen demand; pH; standard plate count; and microscopic examination of the sludge.

Suspended solids were determined by the membrane filter technique described by Engelbrecht and McKinney (36). Metricel G.A.-6 filters with a nominal pore size of 0.45 microns were used. Prior to use, each filter was washed with 100 milliliters of demineralized water, placed in an aluminum weighing dish, and dried at 103°C for 1 hour. After cooling for 1 hour in a dessicator, the aluminum dish and filter were weighed on a type H15 Metller balance. The same drying and weighing procedure was used after the sample was placed on the filter. The precision of the test was checked by replicating 7 trials on a mixed liquor suspended solids sample. The sample mean was 808 mg/L with a standard deviation of ±9.8 mg/L.

The chemical oxygen demand was performed as outlined in Standard Methods (29) for the 10 milliliter sample size. Due to the differences in concentration between the influent wastes and the soluble effluent from the reactor it was necessary to use two modifications of the test. The standard test was used on the influent. The precision of the technique was determined by 10 replications on a sample with an average COD of 772 mg/L. The standard deviation for these tests was ±7 mg/L or 0.9 percent of the mean. The precision of the dilute test was determined by 10 trials on a sample with an average COD of 37.5 mg/L. The standard deviation was ±3.3 mg/L or 8.8 percent of the mean.

The biochemical oxygen demand test was performed as outline for the dilution bottle method in Standard Methods (29). Effluent from the settling tube was used as seed. Tests for precision were not performed.

The pH was measured with a Beckman Model H pH meter. This parameter was monitored to determine if the reaction kinetics during a transition were influenced by pH.

The standard plate count, using serial dilution and spot plate innoculation techniques, was used to determine the change in viable organism concentrations during one series of transitions. Tryptone glucose extract agar incubated at 35°CI 0.5°C for 24 ±2 hour, as specified in Standard Methods (29), was used in making these measurements. Use of the tryptone glucose extract agar in all probability resulted in lower organisms counts than use of a nonselective medium such as the activated sludge extract agar of Prakasam and Dondero (37). However, measuring the absolute number of organisms present was not considered as important in this research as determining the relative change in organism concentration. The technique suggested in Standard Methods was therefore, used in the interests of simplicity and replicability.

Microscopic examination was conducted at 100 and 350 magnification on all cultures used in the research. The purpose of these examinations was to determine the types and relative numbers of bacteria, fungi protozoa, rotifiers, and both free swimming and stalked ciliates present in the culture.

Table 8 - Nutrient Concentrations in the Influent Wastes Used in Both the 3 and the 6-Hour Aeration Only Activated Sludge Experiments*

TOD of waste mg/L	Nitrogen mg/L as N	Phosphorous mg/L as P	Iron** mg/L as Fe	Buffer mg/L as HCO_3
250	83	18.9	2	360.6
500	83	18.9	2	360.6
750	83	18.9	2	360.6
1000	166	37.8	2	721.2
1500	166	37.8	2	721.2

*When a transition was made from 250 to 1000 mg/L COD or from 250 to 1500 mg/L TOD, the dilution water was changed to provide the nutrient concentration called for by the higher strength waste at least two detention times prior to the start of the transition.

**See text for comment on iron concentration used in the synthetic sewage waste

SECTION VI
AERATION ONLY ACTIVATED SLUDGE SYSTEMS

Experimental Conditions

The aeration only studies were conducted in a completely mixed reactor having a liquid volume of 5.28 liters. Aeration and mixing was done with an upflow draft tube. Pumping was provided by three paddles operating in series along a vertical shaft located in the center of the tube. The paddle speed was 475 revolutions per minute. The volume of gas enclosed in the respirometer was 2.27 liters. Carbon dioxide produced by the culture was removed by recirculating this gas through a solution of 10.7 N potassium hydroxide at of 60 ± 10 liters per hour. All tests were conducted at 25 ± 0.25°C.

The activated sludge cultures used were developed by combining approximately 5 liters of fresh settled municipal sewage with the material shown in Table 10.

Table 10. Substrates used in Developing Activated Sludge Cultures for the Aeration Only Experiments.

1.0 gm/L of the carbon source to be studied
0.38 gm/L Ammonium Chloride
0.10 gm/L Potassium Acid Phosphate
0.63 gm/L Sodium bicarbonate
0.01 gm/L Ferrous Sulfate
280 mL of tap water

This mixture was added to the reactor and aerated as a batch system until the exogenous food supply, measured as soluble COD, was consumed. The reactor was then started as a continuous flow system and operated for a minimum of 18 hydraulic mean residence times before starting an experiment. This procedure was very satisfactory for culture acclimation.

Glucose Waste

Fifteen step transient experiments were conducted with the glucose waste. The combinations studied are summarized in Table 11.

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Table 11. Summary of Glucose Waste Transients Investigated in the Aeration Only System

3-Hour Mean Residence Time Influent COD mg/L	6-Hour Mean Residence Time Influent COD mg/L
480 to 250	728 to 481
720 to 260	458 to 725
770 to 275	730 to 242
275 to 494	240 to 735
494 to 719	246 to 498
252 to 747	247 to 950
747 to 250	234 to 1405
252 to 907	

Two distinctive response patterns were observed for step transients involving an increase in influent substrate concentration. The reaction illustrated in Figure 8 is typical of culture response up to approximately a 2 fold substrate increase at the 3-hour mean residence time. This same pattern was observed for up to approximately a 3 fold substrate increase at the 6-hour mean residence time. Over this range of loading the culture was capable of processing the increase in substrate as fast as it entered the reactor and no increase in soluble COD was observed in the effluent. The increase in total COD and in mixed liquor suspended solids was approximately equal to the hydraulic wash in rate for a completely mixed reactor. However, there was very definitely a shift in the growth state of the culture. This was indicated by the rapid increase observed in oxygen utilization. A new steady state oxygen uptake rate was normally established within approximately one hydraulic mean residence time after the start of the transient.

Step increases larger than those cited above produced a response typical to the one illustrated in Figure 9. Under these conditions, substrate entered the reactor faster than the culture could metabolize it and a buildup of soluble COD occurred. This produced exponential growth conditions until the active mass of microorganisms was sufficient to metabolize both the incoming substrate and the food stored in the reactor. Exponential growth continued until the excess substrate in the reactor was consumed and a new steady state balance was established. The increase in oxygen utilization in this type of transition was very rapid and continued

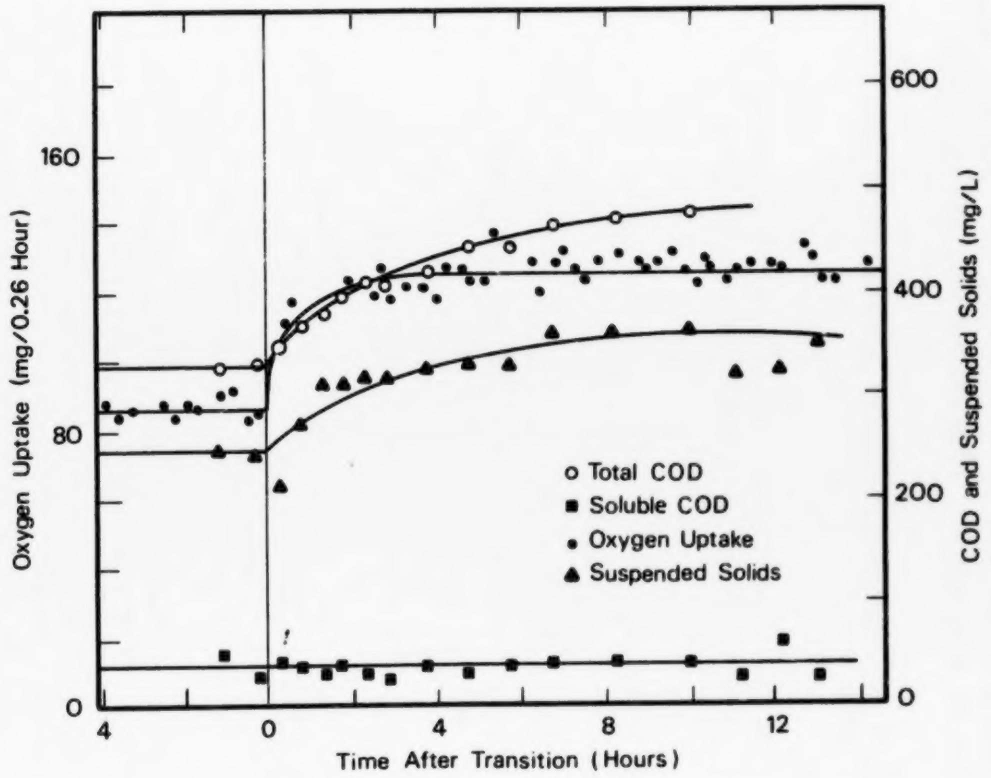

Figure 8. Parameter Response for a Transition from 494 to 719 mg/L Influent COD, Glucose Waste, 3 Hour Mean Residence Time

until equilibrium was reestablished in the system. This resulted in an oxygen uptake peak which was significantly greater than the rate of oxygen utilization observed under steady state conditions.

Summaries of the oxygen uptake response and the corresponding change in soluble COD in the reactor are given in Figures 10 through 13 for all of the step increases conducted on the glucose waste. The reason for the oxygen uptake plateau which occurs from 1 to 3 hours after the start of the transitions illustrated in Figure 12 is not known. However, the explanation may be a shift in species predomination within the culture.

The magnitude of the observed oxygen uptake peaks are summarized in Table 12.

Table 12. Summary of Oxygen Uptake Peaks Observed in the Aeration Only Experiments on Glucose Waste

Mean Residence Time Hours	Magnitude of Change in Influent COD mg/L	Peak Oxygen Uptake mg/L/hr	Percentage of Steady State Oxygen Uptake*
3	252 to 747	112	119
3	252 to 907	155	132
6	234 to 1405	117	133

$$*\frac{\text{Peak Oxygen Uptake Rate}}{\text{Final Steady State Oxygen Uptake Rate}} \times 100$$

The response of an activated sludge culture to a step decrease in influent substrate concentration is illustrated in Figure 14. No change was observed in the effluent soluble COD. The decrease in total COD and in the mixed liquor suspended solids was approximately equal to the hydraulic wash out rate for a completely mixed reactor. The rapid change in oxygen uptake rate again indicated there was definitely a shift in the growth state of the culture. In both the 3 and the 6 hour mean residence time systems a new steady state oxygen uptake rate was usually established within 3 hours. These findings are summarized in Table 13.

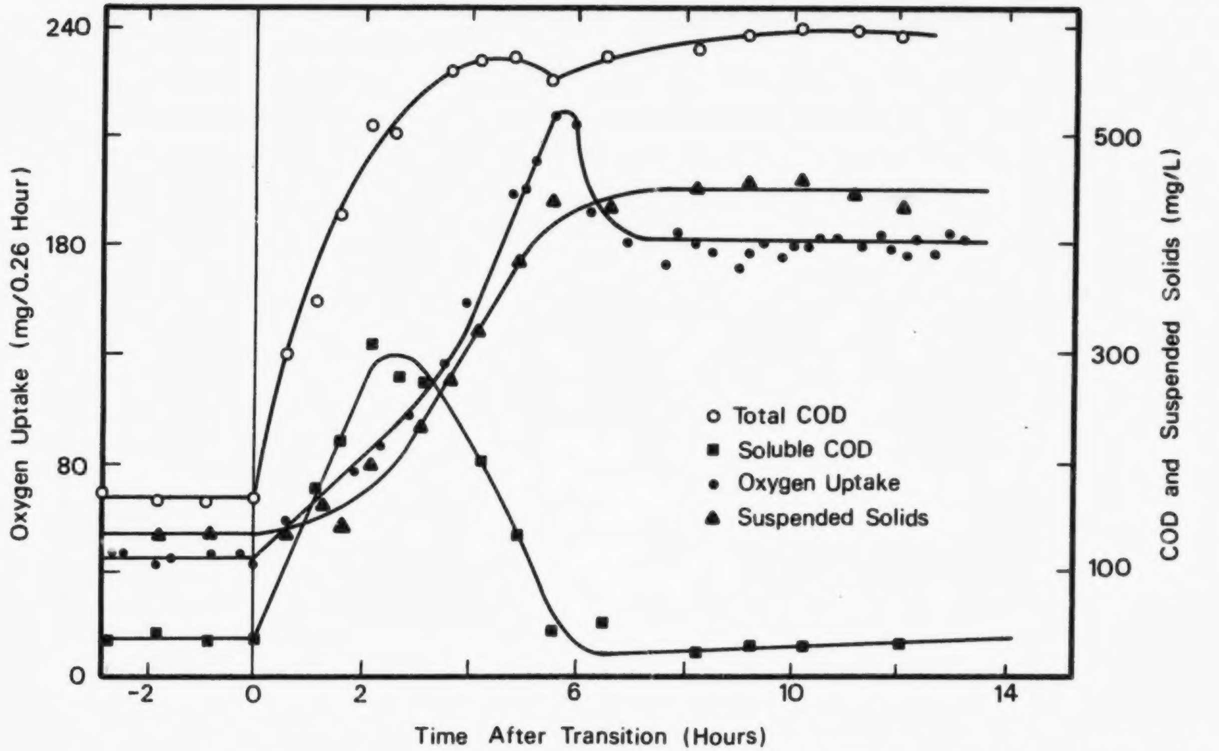

Figure 9. Parameter Response for a Transition from 252 to 907 mg/L Influent COD Glucose Waste, 3 Hour Mean Residence Time

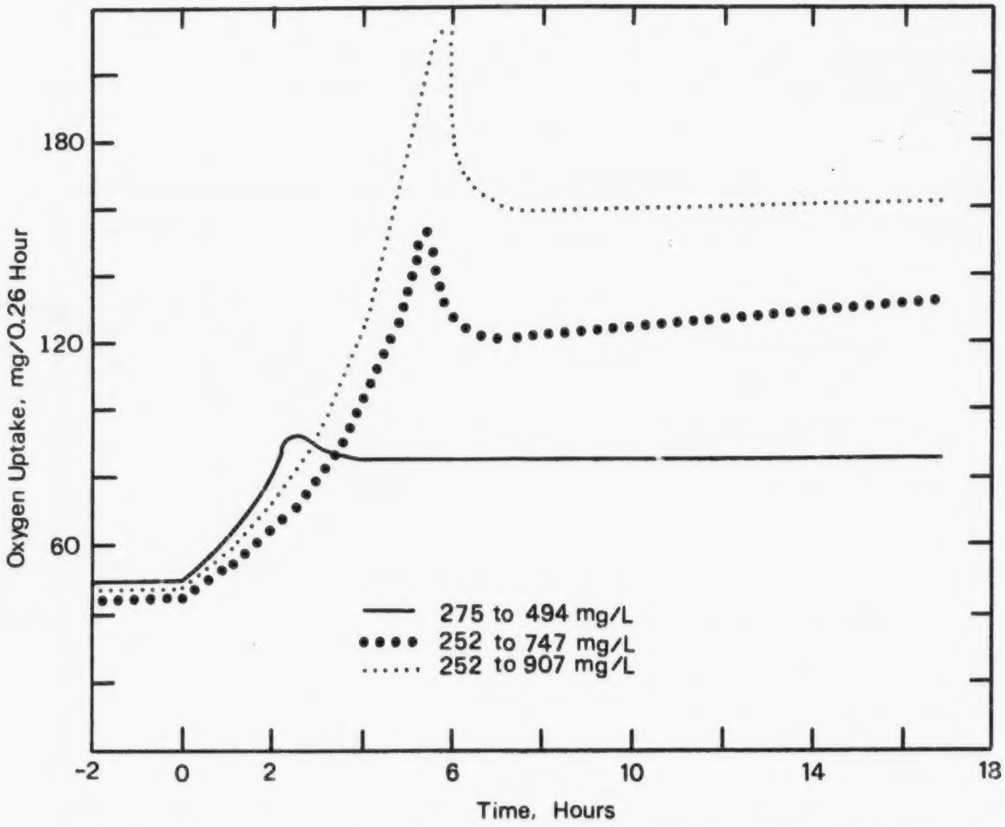

Figure 10. Summary of Changes in Oxygen Uptake Rate in Response to Step Increases in the Influent, Glucose Waste, 3 Hour Mean Residence Time

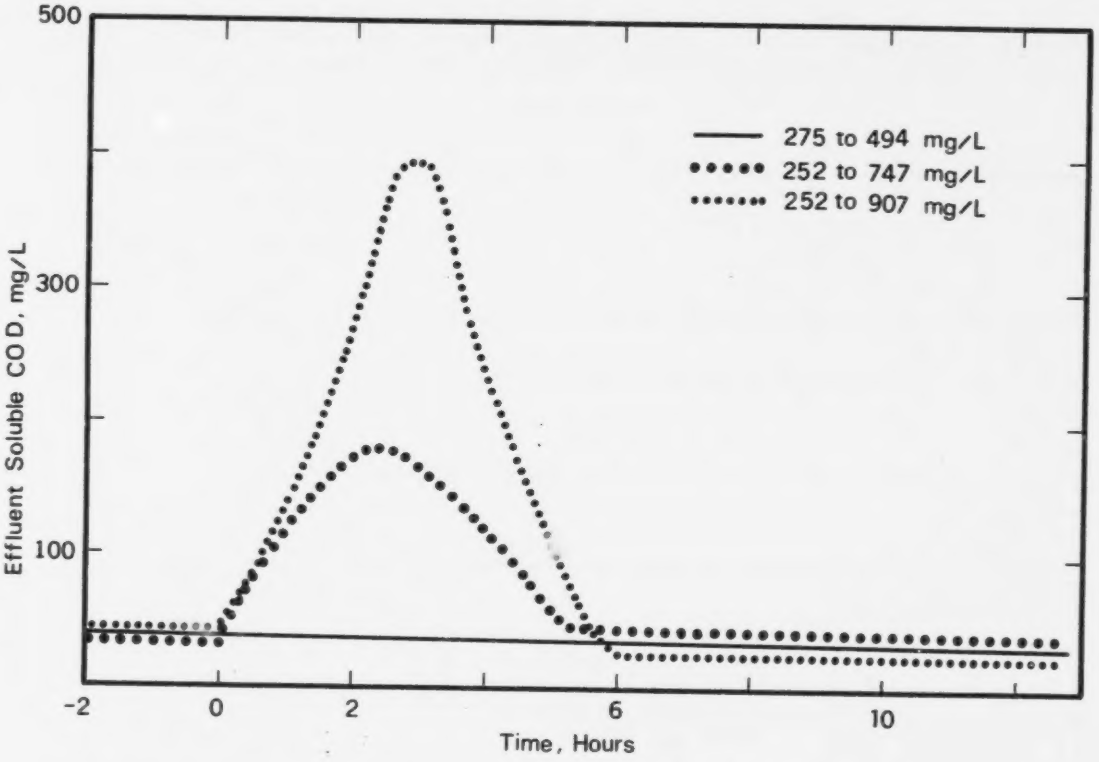

Figure 11. Summary of Changes in Soluble COD Concentration in the Reactor in Response to Step Increases in the Influent, Glucose Waste, 3 Hour Mean Residence Time

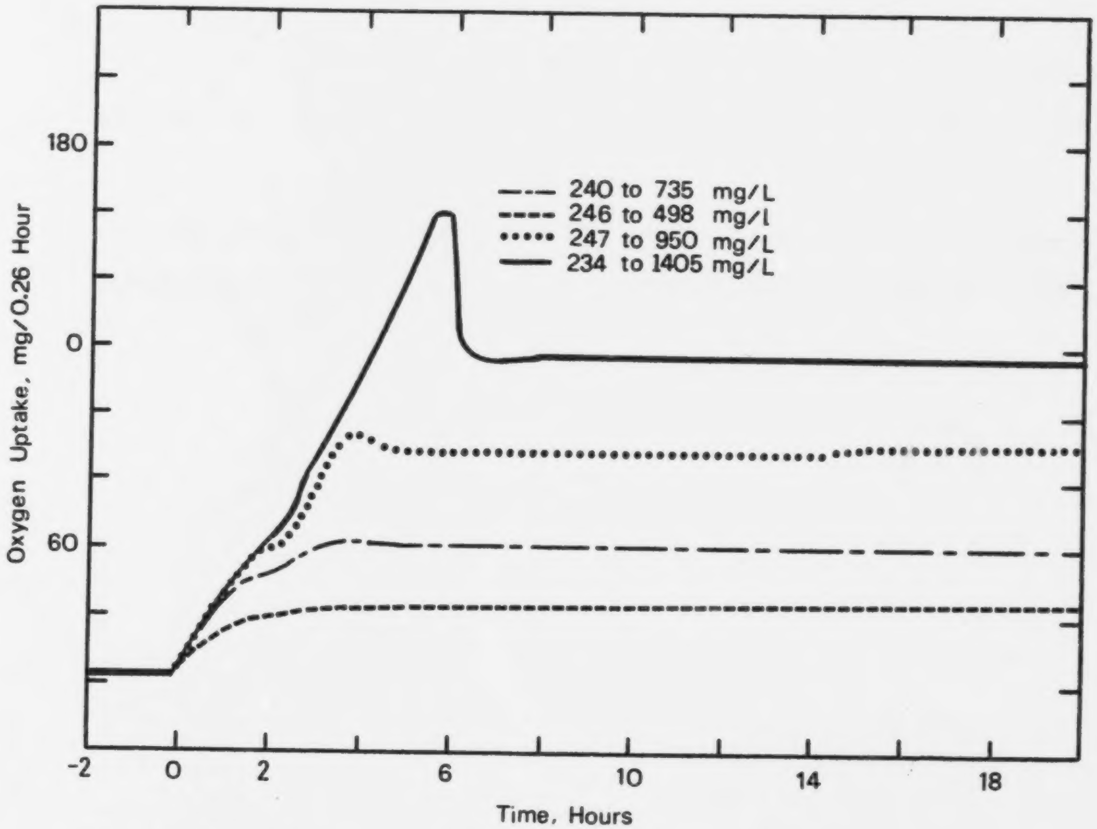

Figure 12. Summary of Changes in Oxygen Uptake Rate in Response to Step Increases in the Influent, Glucose Waste, 6 Hour Mean Residence Time

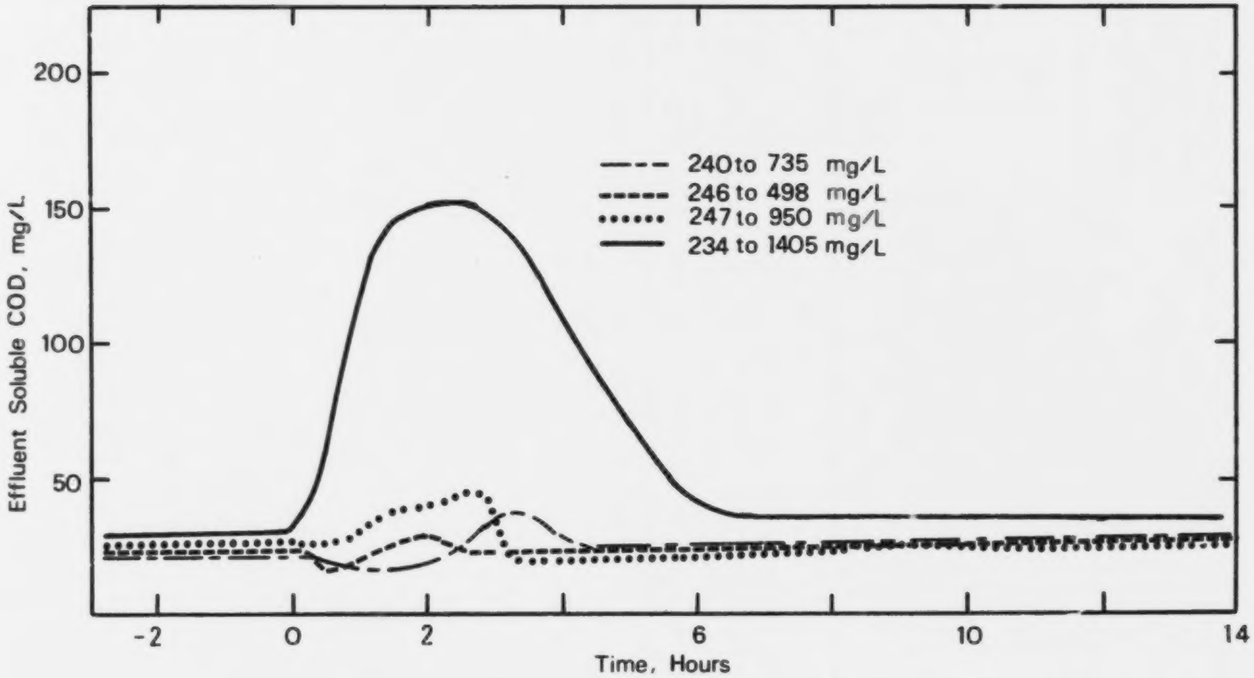

Figure 13. Summary of Changes in Soluble COD Concentration in the Reactor in Response to Step Increases in the Influent, Glucose Waste, 6 Hour Mean Residence Time

Table 13. Summary of Time Required to Establish Steady State Oxygen Uptake Rates After A Step Decrease in Influent Glucose Concentration

Mean Residence Time Hours	Magnitude of Change in Influent COD Concentration mg/L	Time Required to Establish Oxygen Steady State, Hours
3	480 to 250	2.05
3	720 to 260	2.87
3	770 to 275	2.90
3	747 to 250	3.47
6	728 to 481	2.43
6	730 to 242	2.08

The predominate organisms present in the 3-hour mean resident time cultures were highly dispersed bacteria. Some small, free swimming ciliated protozoa were also present. No settling could occur in samples after one hour of quiescent sedimentation. The filterability of the mixed liquor through a 0.45 micron pore size filter was very poor. Up to 50 minutes were required to filter a 15 milliliter sample at the higher suspended solids levels.

The predominate organisms present in the 6-hour mean resident time cultures were fungi. Some small clumps of bacteria were also present. Free swimming ciliates were the predominate higher organisms. Some clarification could be obtained by sedimentation. The filterability of the mixed liquor was markedly better than that obtained at the 3 hour mean residence time.

Standard plate counts using the spot technique were taken during the first 6 hours of the 246 to 498 mg/L COD step increase in the 6-hour mean residence time experiment. The concentration of viable microorganisms increased from 125×10^6 to 200×10^6 per milliliter. The increase in mixed liquor suspended solids during the same interval was 155 to 195 mg/L. These observations indicate the microorganisms were dividing rapidly and the average mass per cell was

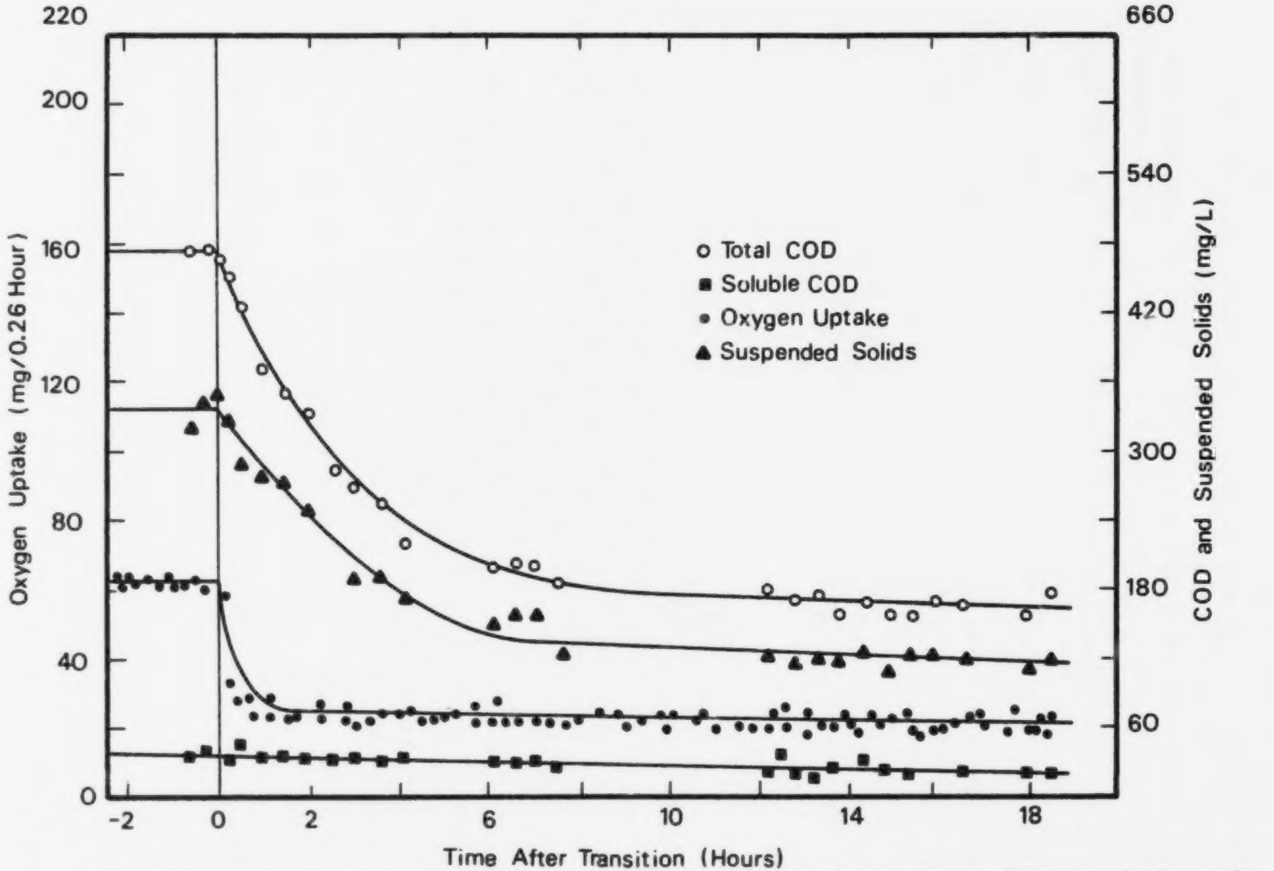

Figure 14. Parameter Response for a Transition from 730 to 242 mg/L Influent COD Glucose Waste, 6 Hour Mean Residence Time

decreasing.

Plate counts were also taken during the first 3 hours of the 720 to 260 mg/L COD step decrease in the 3-hour mean residence time experiment. The concentration of viable microorganisms decreased from 150×10^6 to 120×10^6 per milliliter while the mixed liquor suspended solids decreased from 250 to 150 mg/L. The measurements indicate some inert mass was apparently in the system because the average cell mass is larger than would be normally anticipated. However, the decrease observed in the computed mass per cell fits the reaction expected in a starving culture.

The observations collected for suspended solids and oxygen uptake rate for all periods of steady state operation have been compared with the values predicted for these parameters by the equations developed by McKinney (24). In making these comparisons the influent COD measurements were converted to biochemical oxygen demand (BOD) by the BOD to total oxygen demand (TOD) ratio of Sawyer et al (38) and the COD to TOD ratio of Ballanger et al (39). The conversion factor used was:

$$(16) \quad BOD_5 = 0.76 \text{ COD (Glucose)}$$

The conversion factor used on the first term of equation 13 was also adjusted because it assumes the BOD_5 is 66.7 percent of the ultimate BOD. The work of Sawyer et al (38) indicates the BOD_5 of glucose is 70 percent of the ultimate BOD. The results obtained are presented in Table 14 and Table 15.

The scatter between the predicted and observed suspended solids concentrations is random and within the experimental error associated with COD and SS measurements. The oxygen uptake predictions show a negative bias at the 3-hour mean residence time and positive bias at the 6-hour mean residence time. The source of this systematic error is probably associated with the conversion factor associated with the second term in equation 13. Burkhead and Waddell (40) have shown the compositions of activated sludges are not constant but vary depending upon the stage of growth and the particular organic substrate utilized. This effect can become particularly significant when single carbon source wastes, such as glucose, are being evaluated. However, correcting for this effect was not considered germane to the objective of this research.

Composite Waste

Sixteen step transient experiments were conducted with the

Table 14. Comparison of Observed and Predicted Steady State Suspended Solids Concentration and Oxygen Uptake Rate for the Glucose Waste, 3-Hour Mean Residence Time

Influent COD mg/L	Predicted SS mg/L	Observed SS mg/L	% Error	Predicted O_2 mg/L/hr	Observed O_2 mg/L/hr	% Error
480	232	247	- 6.1	57	57	0
250	121	137	-11.7	30	31	- 3.2
720	349	260	+34.2	85	83	+ 2.4
260	125	125	0	31	35	-11.4
770	373	325	+14.8	91	90	+ 1.1
275	133	113	+17.7	32	36	-11.1
494	240	245	- 2.0	58	63	- 7.9
719	349	341	+ 2.3	85	93	- 8.6
252	123	129	- 4.7	29	34	-14.7
747	361	318	+13.5	89	94	- 5.3
907	439	449	- 2.2	108	117	- 7.7

Table 15. Comparison of Observed and Predicted Steady State Suspended Solids Concentration and Oxygen Uptake Rate for the Glucose Waste, 6-Hour Mean Residence Time

Influent COD mg/L	Predicted SS mg/L	Observed SS mg/L	% Error	Predicted O_2 mg/L/hr	Observed O_2 mg/L/hr	% Error
728	333	341	- 2.3	51	43	+18.6
481	221	187	+18.2	33	31	+ 6.5
458	210	187	+12.3	32	27	+18.5
725	333	328	+ 1.5	50	47	+ 6.4
730	333	338	- 1.5	51	46	+10.9
242	112	120	- 6.7	17	15	+13.3
240	109	124	-12.1	17	16	+ 6.2
735	337	320	+ 5.3	51	44	+15.9
246	112	-	-	17	17	0
498	228	267	-14.6	35	33	+ 6.1
247	112	126	-11.1	18	16	+12.5
950	434	415	+ 4.6	66	70	- 5.7
234	109	117	- 6.8	16	16	0
1405	644	678	- 5.0	98	88	+11.4

composite waste. The combinations studied are summarized in Table 16.

Table 16. Summary of Composite Waste Transients Investigated in the Aeration Only System

3-Hour Mean Residence Time Influent COD mg/L	6-Hour Mean Residence Time Influent COD mg/L
214 to 411	250 to 504
411 to 194	504 to 235
194 to 651	235 to 736
652 to 480	226 to 1480
478 to 717	1480 to 258
717 to 245	258 to 1003
245 to 974	
974 to 241	
241 to 1460	
253 to 750	

Transient response was very similar to that exhibited by the glucose waste. Two fold step increases at the 3 hour mean residence time and 3 fold step increases at the 6 hour mean residence time produced responses similar to those illustrated in Figure 8. Larger step increases resulted in the leakage of soluble COD in the reactor effluent and produce transient peaks in the oxygen uptake rate.

Summaries of the oxygen uptake response and the corresponding change in soluble COD in the reactor are given in Figure 15 through 18. The most interesting transition was the one from 226 to 1480 mg/L COD at the 6 hour mean resident time. Complete data for this experiment is illustrated in Figure 19. The plateau in oxygen utilization observed in the glucose runs was present. In addition, two temporary decreases in oxygen uptake occured at about 8.8 and 10.6 hours after the start of the transition. Each of these decreases was approximately one hour in length. These small peaks, superimposed on the general oxygen utilization response, suggest possible sequential substrate removal as discussed by Gaudy et al (41). This possibility should be more fully investigated.

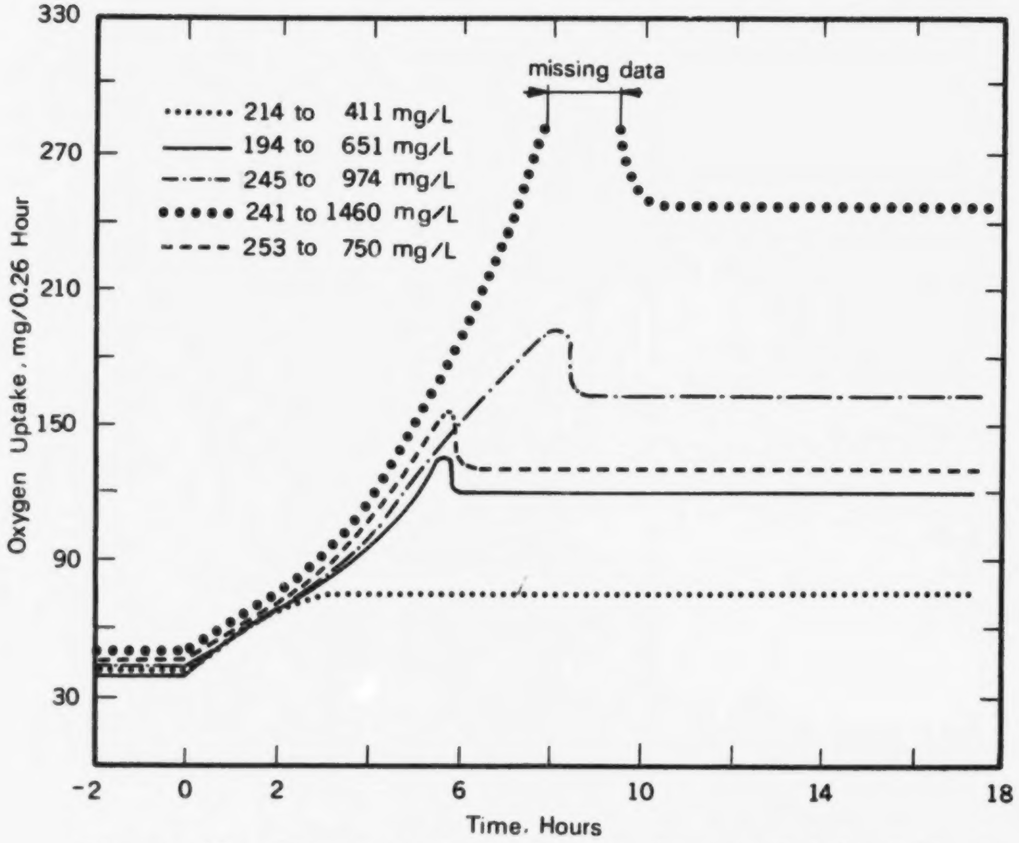

Figure 15. Summary of Changes in Oxygen Uptake Rate in Response to Step Increases in the Influent, Composite Waste, 3-Hour Mean Residence Time

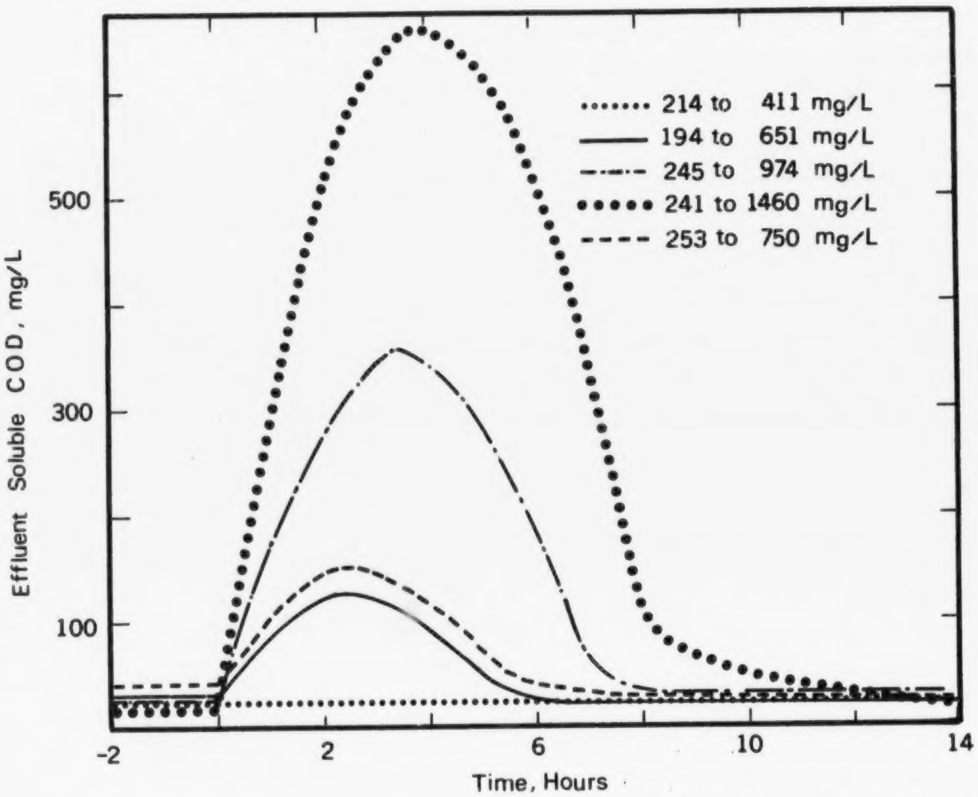

Figure 16. Summary of Changes in Soluble COD Concentration in the Reactor in Response to Step Increases in the Influent, Composite Waste, 3-Hour Mean Residence Time

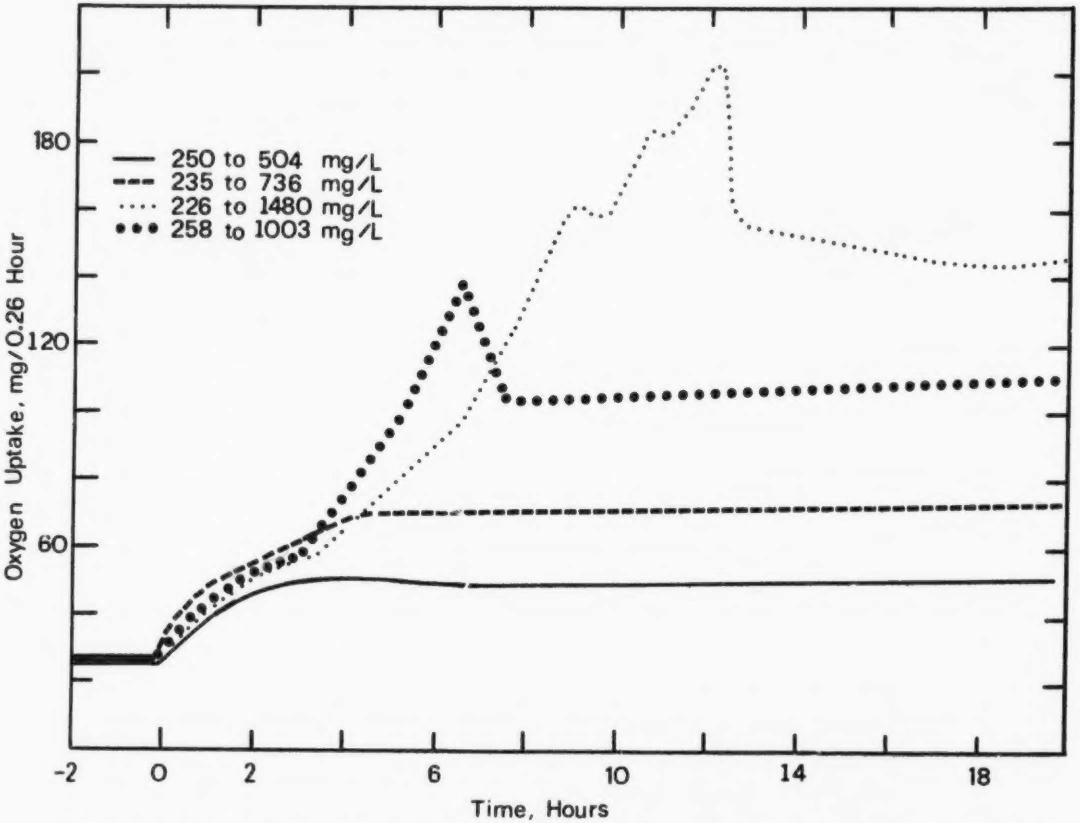

Figure 17. Summary of Changes in Oxygen Uptake Rate in Response to Step Increases in the Influent, Composite Waste, 6 Hour Mean Residence Time

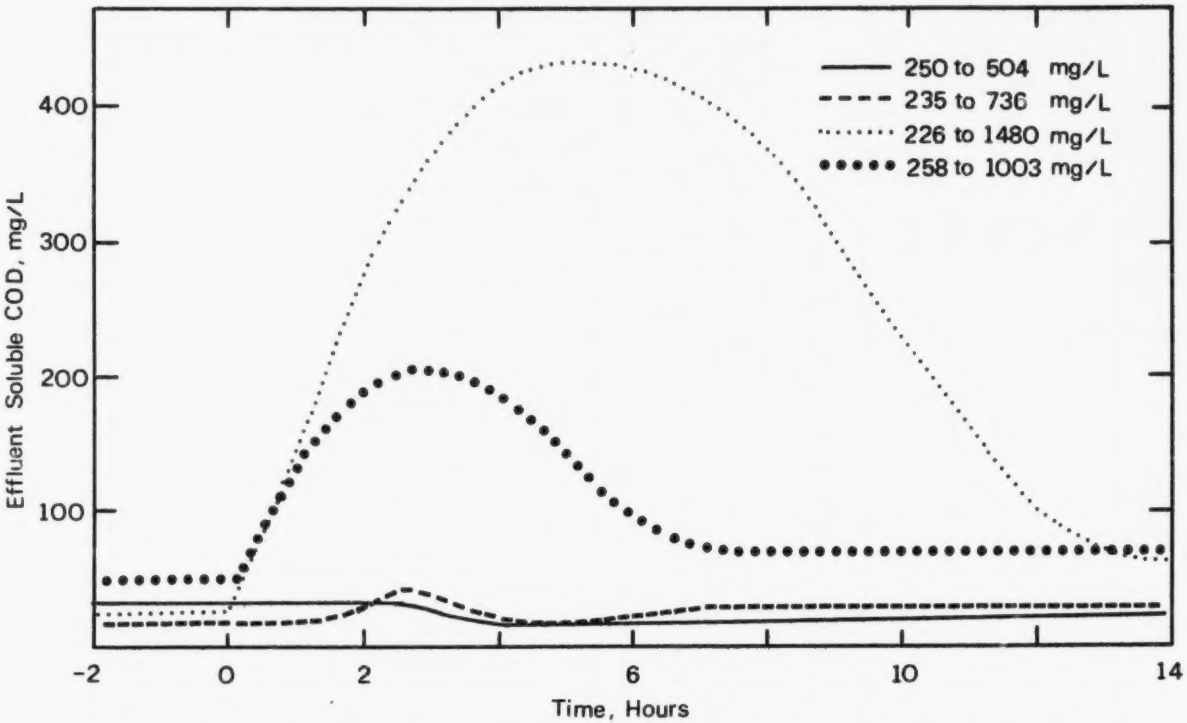

Figure 18. Summary of Changes in Soluble COD Concentration in the Reactor in Response to Step Increases in the Influent, Composite Waste, 6 Hour Mean Residence Time

The magnitude of the observed oxygen uptake peaks are summarized in Table 17.

Table 17. Summary of Oxygen Uptake Peaks Observed in the Aeration Only Experiments Conducted on the Composite Waste

Mean Residence Time Hours	Magnitude of Change in Influent COD mg/L	Peak Oxygen Uptake mg/L/hr	Percentage of Steady State Oxygen Uptake*
3	194 to 651	98	110
3	253 to 750	114	123
3	245 to 974	140	120
6	248 to 1003	102	150
6	226 to 1480	151	137

$$*\frac{\text{Peak Oxygen Uptake Rate}}{\text{Final Steady State Oxygen Uptake Rate}} \times 100$$

The transition from 253 to 750 mg/L COD at the 3-hour mean residence time was made specifically to evaluate the effects of oxygen limiting conditions. At the start of the experiment the partial pressure of oxygen in the reactor was lowered so dissolved oxygen levels approaching zero would be observed during the peak demand period. The concentration of dissolved oxygen decreased to 0.5 mg/L 3.5 hours after the start of the transition and remained below this value for approximately 3.5 hours. The minimum concentration observed was 0.1 mg/L which occurred for one hour during the period of peak oxygen uptake rate by the culture. On the basis of the data prssented in Table 17 and Table 19, it did appear the period of low dissolved oxygen concentration did not have a deleterious effect on the system. Thabara, and Gaudy (42) have reported partial culture failure during transient conditions in a glucose system operating on an 8-hour mean residence time.

The response to a step decrease in influent substrate is illustrated in Figure 20. Culture behavior was identical to that observed for the glucose waste with a new steady state oxygen uptake rate usually established within 3 hours. The major exception to this rule was the decrease from 1480 to

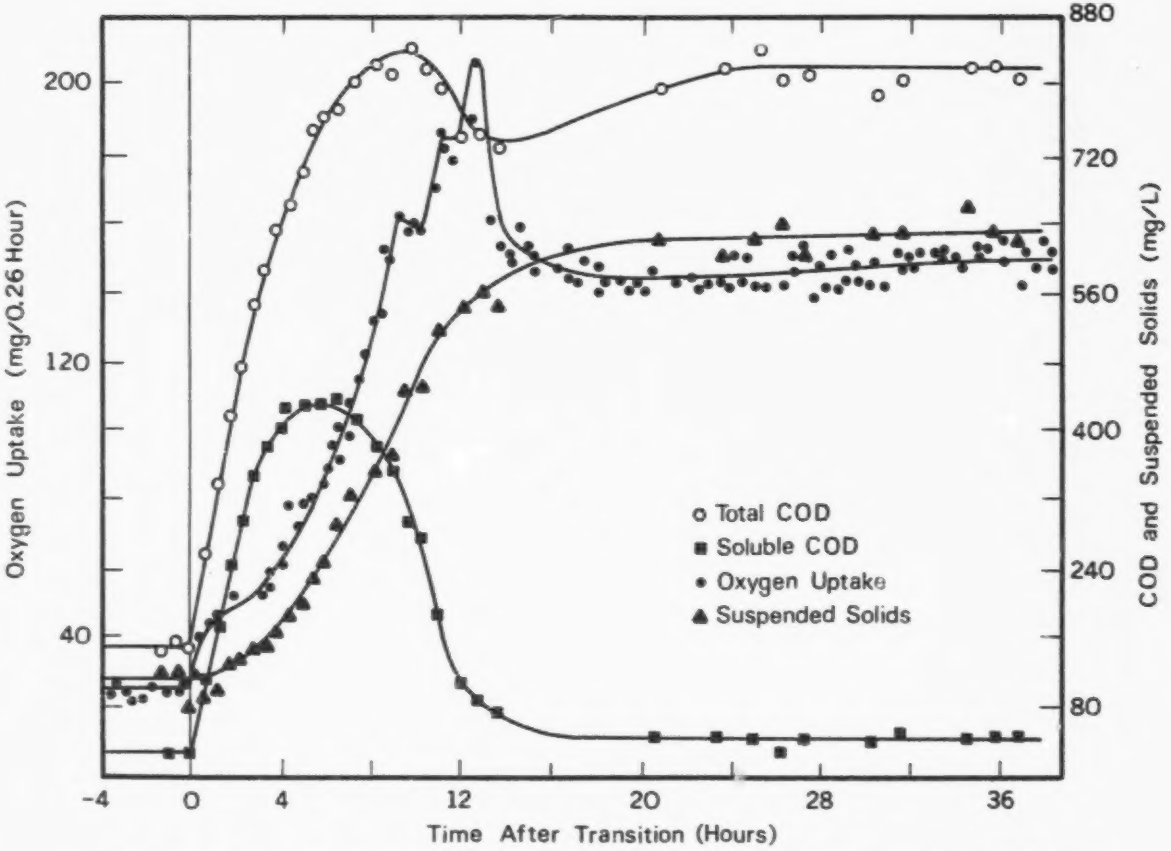

Figure 19. Parameter Response for a Transition from 226 to 1480 mg/L Influent COD, Composite Waste, 6-Hour Mean Residence Time

to 258 mg/L COD which required 4.72 hours. These findings are summarized in Table 18.

Table 18. Summary of Time Required to Establish Steady State Oxygen Uptake Rates After a Step Decrease in Composite Waste Concentration.

Mean Residence Time Hours	Magnitude of Change in Influent COD Concentration mg/L	Time Required to Establish Oxygen Steady State, Hours
3	411 to 194	1.29
3	652 to 480	2.88
3	717 to 245	3.08
3	974 to 241	2.85
6	504 to 235	1.30
6	1480 to 258	4.72

Actinomycetes, fungi, and small clumps of bacterial floc were observed in the 3-hour mean residence time cultures. Free swimming ciliates were the predominant higher organism. A small shift in predomination by fungi occured in the 6-hour mean residence time culture.

Sedimentation did not occur in the 3-hour culture but was present to some degree in the 6-hour system. The filterability of the 6 hour culture was very good with from 30 seconds to 3 minutes required to dewater 15 milliliters of MLSS.

The observations collected for suspended solids and oxygen uptake rate for all periods of steady state operation have been compared with the values predicted for these parameters by the equations developed by McKinney (24). In making these comparisons the influent COD measurements were converted to biochemical oxygen demand (BOD) by the BOD to total oxygen demand (TOD) ratio of Sawyer et al (38) and the COD to TOD ratio of Ballanger et al (39) for the glucose and the glutamic acid. Adjustment for the acetic acid was based on the BOD to TOD ratio of Gaffney and Heukelekian (43). The computed conversion equation was:

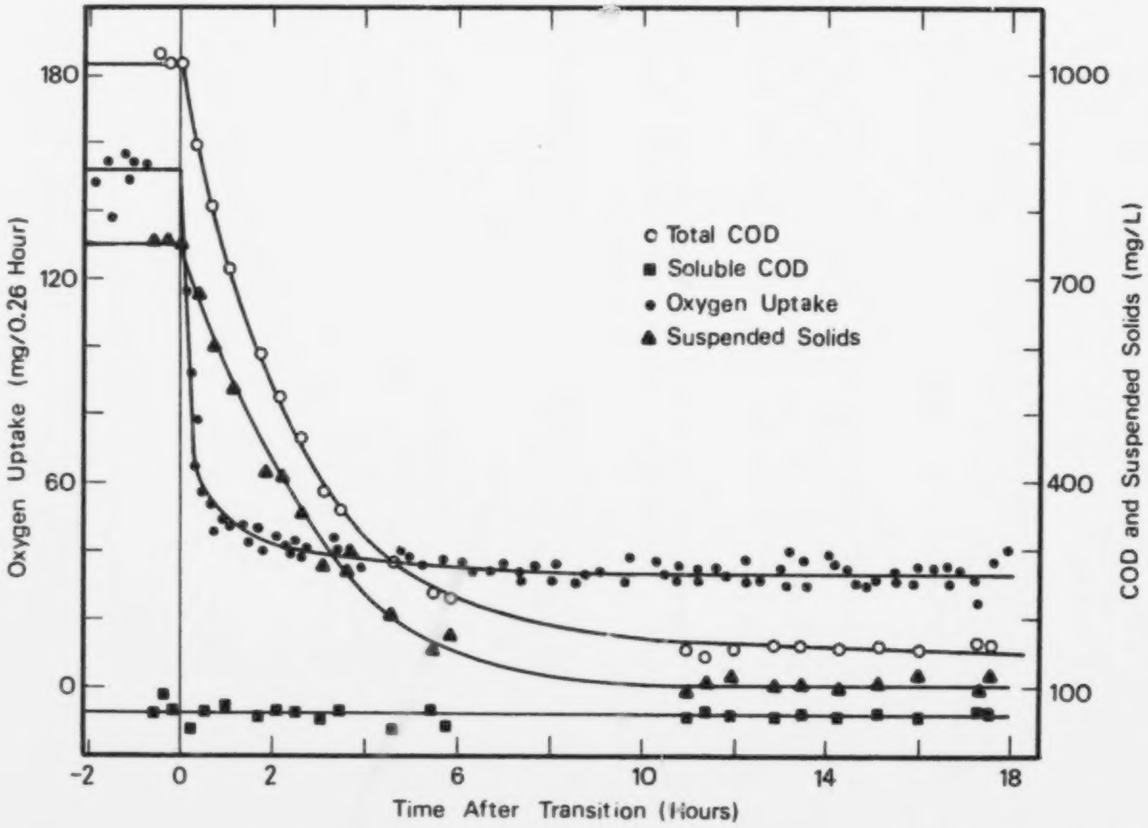

Figure 20. Parameter Response for a Transition from 1480 to 258 mg/L Influent COD, Synthetic Sewage, 6 Hour Mean Residence Time

$$(17)\ BOD_5 = 0.77\ COD\ (Composite)$$

This agrees well with the experimentally measured coefficient of 0.76.

The conversion factor on the first term in equation 13 was adjusted in this instance because the work of Sawyer et al (38) indicates the BOD_5 of a mixture of glucose and glutamic acid is 69.6 percent of the ultimate BOD. The results obtained are given in Table 19 and Table 20.

The suspended solids measurements associated with 258 and 736 mg/L COD in Table 20 appear to be in error. With these exceptions, the scatter between the predicted and observed suspended solids concentrations in both tables is within expected experimental error.

The predicted oxygen uptake values have a consistent negative bias in both tables. This probably reflects an error in the conversion factor adjustment in equation 13. Use of the 1.5 conversion results in a consistent positive bias of approximately the same magnitude.

Synthetic Sewage - Seven step transients were conducted with the synthetic sewage. The combinations studied are summarized in Table 21.

Table 21. Summary of Synthetic Sewage Transients Investigated in the Aeration Only System.

3-Hour Mean Residence Time Influent COD mg/L	6-Hour Mean Residence Time Influent COD mg/L
249 to 433	214 to 316
233 to 690	176 to 615
233 to 864	169 to 1420
189 to 1200	1410 to 190

The process used to prepare the synthetic sewage produced a solution which contained a significant concentration of

Table 19. Comparison of Observed and Predicted Steady State Suspended Solids Concentration and Oxygen Uptake Rate, Composite Waste, 3-Hour Mean Residence Time

Influent COD mg/L	Predicted SS mg/L	Observed SS mg/L	% Error	Predicted O_2 mg/L/hr	Observed O_2 mg/L/hr	% Error
214	105	100	+ 5.0	26	28	- 7.1
411	201	191	+ 5.2	50	54	- 7.4
194	95	110	-13.6	24	28	-14.2
651	318	323	- 1.5	80	89	-10.1
478	234	223	+ 4.9	58	62	- 6.5
717	351	280	+25.4	86	93	- 7.5
245	121	106	+14.2	29	36	-19.4
974	477	448	+ 6.5	117	117	0
241	119	122	- 2.5	29	31	- 6.4
1460	715	733	- 2.5	176	179	- 1.7
253	123	124	- 0.8	31	34	- 8.8
750	367	321	+14.3	90	93	- 3.2

Table 20. Comparison of Observed and Predicted Steady State Suspended Solids Concentration and Oxygen Uptake Rate, Composite Waste, 6-Hour Mean Residence Time

Influent COD mg/L	Predicted SS mg/L	Observed SS mg/L	% Error	Predicted O_2 mg/L/hr	Observed O_2 mg/L/hr	% Error
250	116	114	+ 1.7	18	18	0
504	251	205	+22.4	38	36	+ 5.6
235	109	94	+16.0	17	19	-10.5
736	341	255	+33.7	52	58	-10.3
226	105	113	- 7.0	16	19	-15.8
1480	685	626	+ 9.4	105	110	- 4.5
258	120	84	+42.9	19	23	-17.4
1003	464	398	+16.6	71	68	+ 4.4

colloidal particles. This presented experimental difficulties because the metering pumps used to add the waste to the reactor were frequently clogged by the particulate material. This problem was especially acute during the 3-hour mean residence time experiments because the waste was pumped as the concentrated solution. The problem was partially alleviated in the 6-hour mean residence time transients by mixing the concentrated waste with the dilution water and pumping the mixture.

The data obtained with substrate were well worth the experimental problems, however, because they clearly illustrate differences between the reaction kinetics of cultures utilizing relatively simple soluble substrates and those fed a complex mixture of soluble and suspended organic material.

The response of a culture to a 6-fold step increase in the influent substrate concentration is illustrated in Figure 21. The significant differences between this transient and those observed earlier are:

(a) The magnitude of the soluble COD peak observed in the reactor effluent was significantly less than those observed for comparable transients in the glucose and composite waste experiments. This reflects the earlier comment regarding the mixture of soluble and insoluble components in the total COD of the synthetic sewage.

(b) The buildup of the soluble COD in the reactor was largely controlled by the hydraulics of the system and therefore closely resembles the shape of the increases observed during transients in the glucose and the composite waste experiments. However, the decrease in the soluble COD in the reactor was much slower for the synthetic sewage than those observed for the other wastes. This slow decrease in the soluble COD was probably caused by hydrolysis of the suspended organic material present in the influent.

(c) The increase in suspended solids and in oxygen utilization was much slower for step transients using the synthetic sewage than were observed those for comparable transients in the glucose and the composite waste. This is probably also caused by the hydrolysis reactions mentioned above.

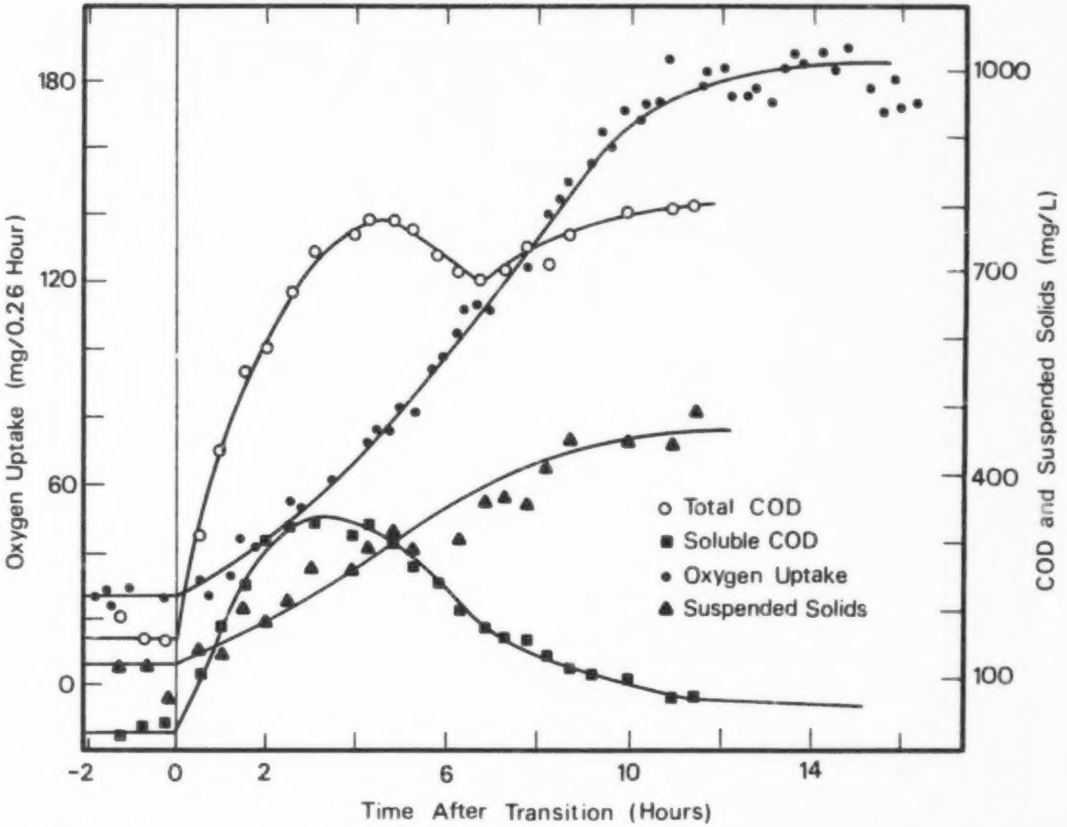

Figure 21. Parameter Response for a Transition from 189 to 1200 mg/L Influent COD, Synthetic Sewage, 3 Hour Mean Residence Time

Summaries of the results observed for oxygen utilization and soluble COD in the reactor effluent are given for all of the transients studied in Figures 22 through 25. The data presented in Figure 22 reflects the difficulties with pump clogging mentioned earlier. The missing data in this figure was caused by this factor. The apparent decrease in the oxygen uptake rate following a period of missing data may be in error.

The 3-hour mean residence time system was capable of responding to a 2-fold step increase in the influent substrate concentration without a change in the concentration of the soluble COD in the reactor effluent. The evidence is inconclusive for the 6-hour mean residence time system because the response of the culture appeared to be erratic. However, at the present time, doubling the concentration in the influent appears to be the maximum change the culture can withstand without producing an increase in soluble COD in the reactor.

Distinct oxygen uptake peaks were not observed when the change in the influent substrate concentration was large enough to produce peaks of soluble COD in the reactor effluent. There is some evidence of smaller magnitude relatively long duration peaks in oxygen utilization during the 3-hour mean residence time experiments. However, when these peaks do exist their magnitude appears to be within 10 percent of the steady state oxygen utilization rate.

One step decrease in the influent substrate was conducted with the 6-hour mean residence time system. Culture behavior was very similar to that observed for the glucose and the composite wastes. No change occured in the soluble COD concentration. The decrease in total COD and in the mixed liquor suspended solids was approximately equal to the hydraulic wash out time. The decrease in the oxygen utilization rate was quite rapid. A new steady state was established approximately 6 hours after the start of the transient. This is somewhat longer then the time required for a comparable transient with the composite waste. The difference is probably due to the hydrolysis of particulate matter in the synthetic sewage.

The predominate organisms present in the 3-hour mean residence time system were dispersed bacteria. Some fungi and a few small free swimming protozoa were present. In the 6-hour mean residence time experiments the bacterial mass shifted from a predominance of bacterial floc with a few actinomycetes, and stalked and free swimming cilitates at the start of the experiments to a predominance of fungi and very

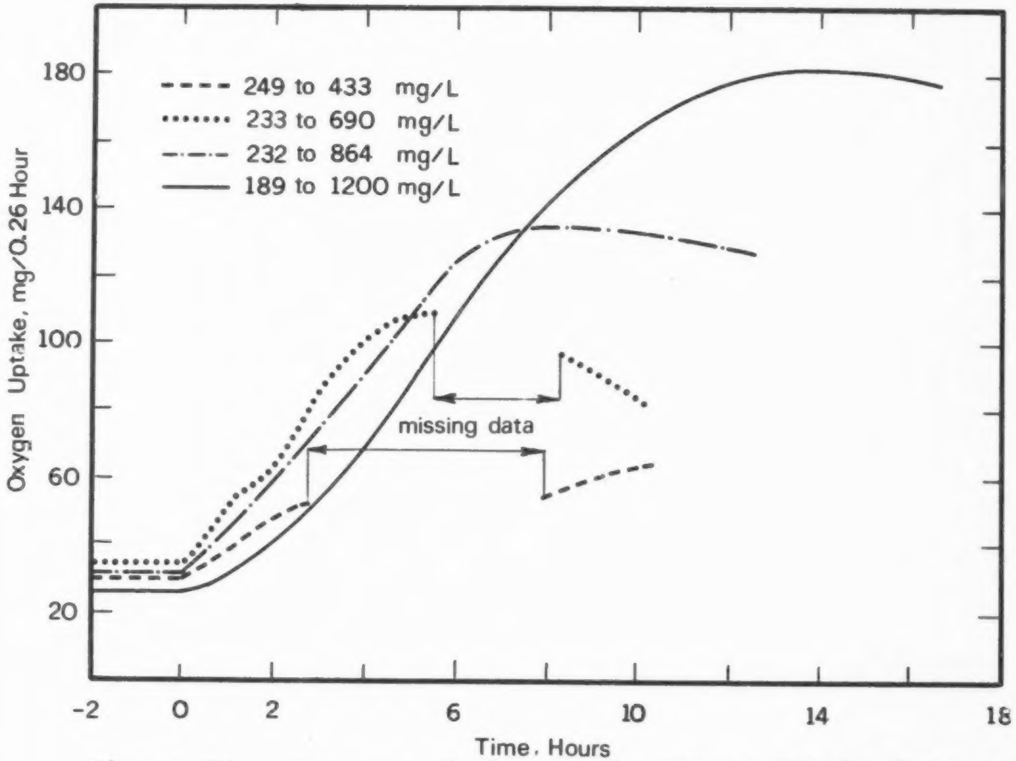

Figure 22. Summary of Changes in Oxygen Uptake Rate in Response to Step Increases in the Influent, Synthetic Sewage, 3-Hour Mean Residence Time

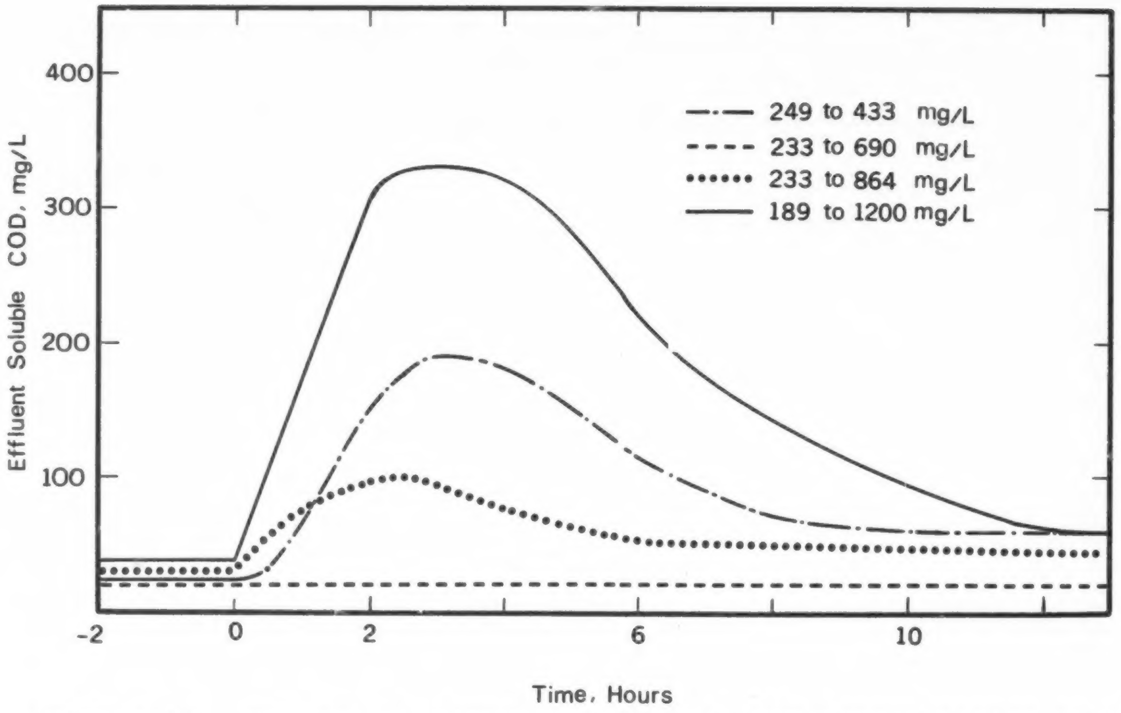

Figure 23. Summary of changes in Soluble COD Concentration in the Reactor in Response to Step Increases in the Influent, Synthetic Sewage, 3 Hour Mean Residence Time

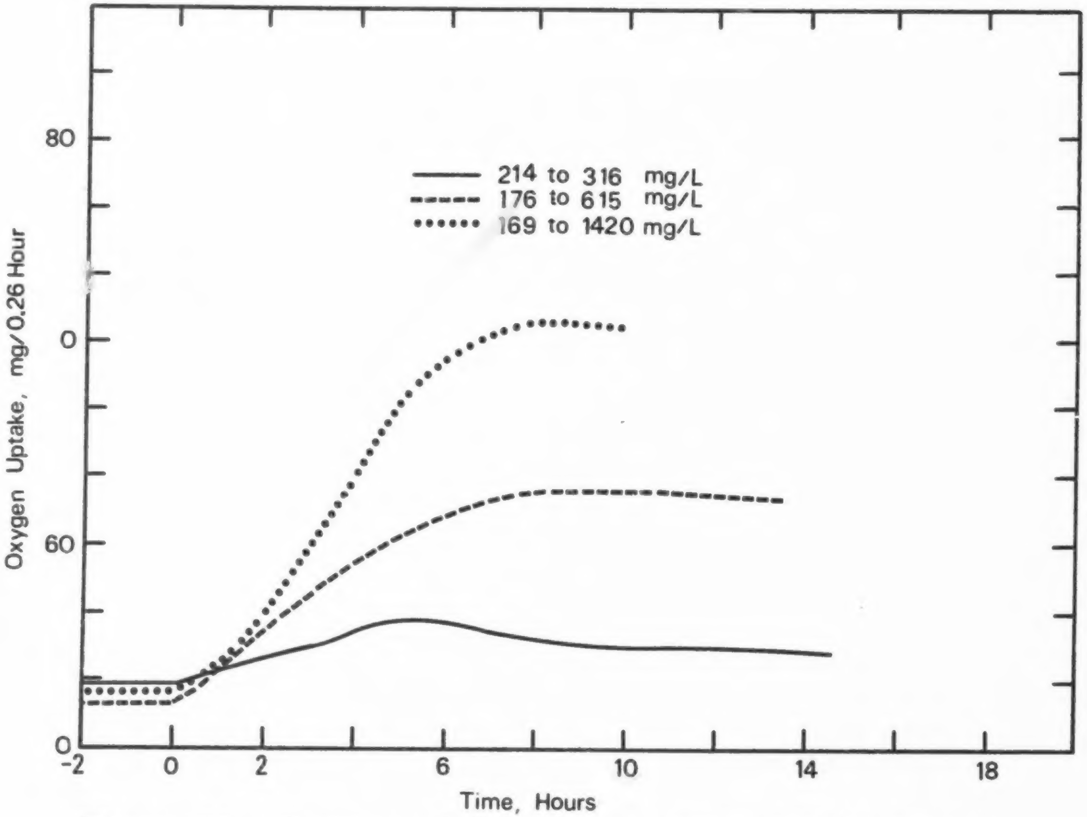

Figure 24. Summary of Changes in Oxygen Uptake Rate in Response to Step Increases in the Influent, Synthetic Sewage, 6 Hour Mean Residence Time

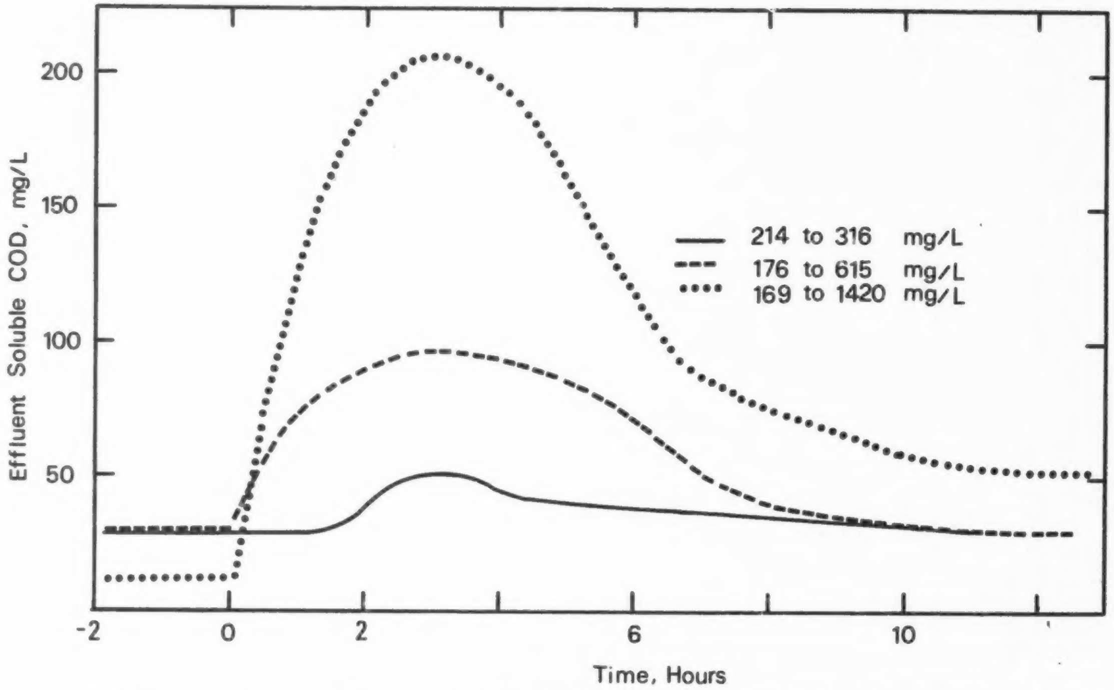

Figure 25. Summary of Changes in Soluble COD Concentration in the Reactor in Response to Step Increases in the Influent, Synthetic Sewage, 6 Hour Mean Residence Time

small free swimming ciliates at the end. The presence of microorganisms in the synthetic sewage concentrate may have contributed to these population shifts.

A biochemical oxygen demand (BOD) to chemical oxygen demand (COD) ratio was not measured for the synthetic sewage so a comparison between the observed and predicted suspended solids concentration and oxygen utilization rate was not possible. Observed steady state values are given in Table 22.

Table 22. Observed Steady State Suspended Solids and Oxygen Uptake Rates for Synthetic Sewage

3-Hour Mean Residence Time			6-Hour Mean Residence Time		
Influent COD mg/L	Suspended Solids mg/L	Oxygen Uptake mg/L/hr	Influent COD mg/L	Suspended Solids mg/L	Oxygen Uptake mg/L/hr
189	102	20	169	162	15
233	120	24	176	133	9
249	117	23	214	122	14
265	153	30	615	344	53
864	438	93	1410	573	87
1200	-	130			

The 3-hour mean residence time observations correspond closely to the values reported for the glucose and the composite wastes. The value of 169 mg/L influent COD reported for the 6-hour mean residence time appears to be in error. Both the suspended solids and the oxygen uptake observations indicate the COD concentration was approximately 200 mg/L.

Discussion

Transient response for the glucose and the composite wastes were very similar. Large increases in the influent substrate concentration produced conditions analogous to the classical response observed in batch cultures immediately after the addition of a large amount of food.

The first reaction in the culture was a short period of adjustment or acclimation. This was followed by period of exponential growth which continued until the excess exogenous food supply was exhausted. The culture then rapidly shifted into declining growth and a new steady state was established. The sequence of this reaction is illustrated in Figure 26 which summarizes the suspended solids observations for the upward transients conducted at the 3-hour mean residence time for the composite waste. The suspended solids observations have been plotted on a logrithmic scale to illustrate the change in growth rate.

The end of exponential growth was determined for each of the upward transients during which it occured by the graphical procedures illustrated in Figure 26. This information was combined with concurrent observations of the soluble COD in the reactor to produce graphs similar to the one illustrated in Figure 27. The estimates obtained by this process for the critical food to mass (F/M) ratio for the glucose and the composite wastes at 25°C are summarized in Table 23.

Table 23. Food to Mass Ratios Observed at the Transition from Exponential to Declining Growth for the Glucose and the Composite Wastes

3-Hour Mean Residence Time		6-Hour Mean Residence Time	
Waste	F/M*	Waste	F/M*
Glucose	0.58	Glucose	0.50
Glucose	0.48	Composite	0.55
Composite	0.43		
Composite	0.40		
Composite	0.27		

$$*F/M = \frac{\text{soluble COD mg/L}}{\text{suspended solids mg/L}}$$

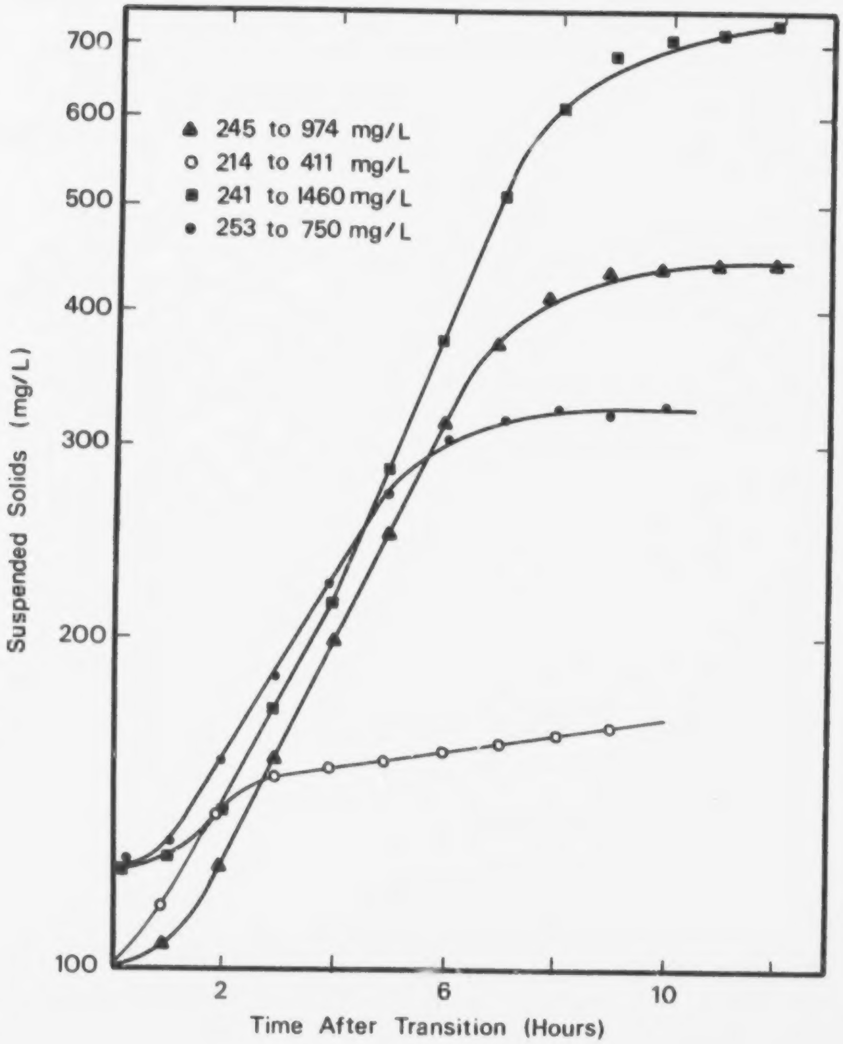

Figure 26. Summary of the Suspended Solids Observations for the Upward Transients Conducted at the 3-Hour Mean Residence Time for the Composite Waste

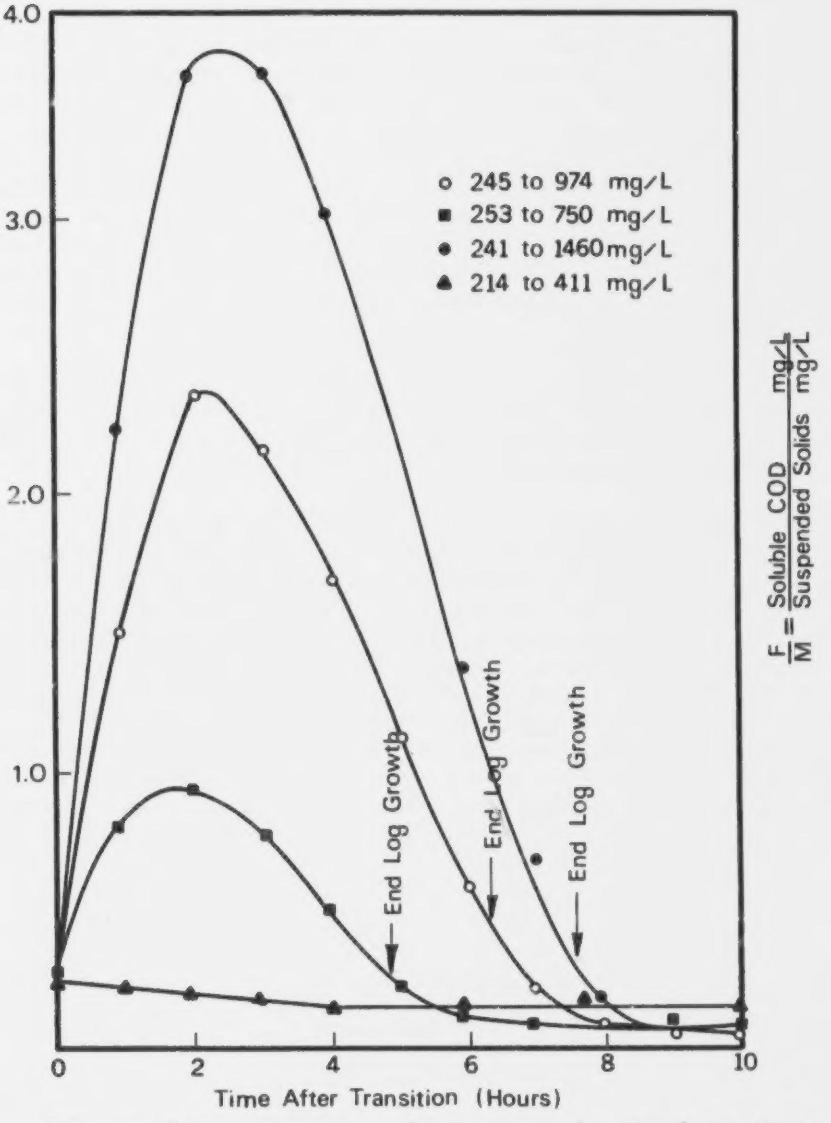

Figure 27. Summary of Changes in Food to Mass Ratios for the Upward Transients Conducted at the 3-Hour Mean Residence Time for the Composite Waste

The COD measurements used to determine the (F/M) ratios in Table 23 include some nonbiodegradable end products in addition to soluble biodegradable substrate. To be completely valid, (F/M) ratios should be based on ultimate BOD rather than COD. However, COD is the most practical method of measuring the concentration of soluble organic material in continuous flow systems.

The critical (F/M) ratios given in Table 23 are significantly lower than the corresponding values reported for batch systems (23). There are two reasons for this: one is the difference in the rate of culture response for simple soluble substrates and for complex substrates containing both soluble and suspended material. The second reason involves the constant addition of substrate which occurs in a continuous flow system. A continuous culture has available to it over any given time interval the substrate already in the reactor plus the substrate entering the reactor during that time interval.

The concept of the food to mass (F/M) ratio should therefore be revised to include the rate of organic loading, the type of substrate, and the temperature. This is an area which requires further research.

The oxygen uptake rate during transients which involved exponential growth included a characteristic transient peak which in this research ranged from 119 to 150 percent of the new steady state. The period of maximum oxygen utilization occured after the culture had shifted from exponential to declining growth with the peak usually coinciding with the point at which the soluble COD in the reactor returned to a new equilibrium. The rate of decrease in oxygen utilization from the peak to the new steady state was extremely rapid and appears to be quite analogous to the response relationship observed throughout the aeration only experiments following a step decrease in the influent substrate.

SECTION VII
AERATION WITH SLUDGE RETURN ACTIVATED SLUDGE SYSTEMS

Experimental Conditions

The aeration with sludge return experiments were conducted in a completely mixed reactor having a liquid volume of 10.00 liters. An upflow draft tube was used for aeration and mixing. The liquid was pumped through the tube by two paddles rotating at 400 revolutions per minute. The respirometer contained 2.55 liters of gas above the surface of the liquid. This gas was recirculated through a scrubber containing a solution of 10.7 N potassium hydroxide to remove the carbon dioxide produced by the culture. The gas pumping rate was 60±10 liters per hour. The aeration basin was followed by a sedimentation basin with a 2-hour hydraulic detention time. Sludge was continuously recirculated from the sedimentation basin back to the aeration basin. All experiments were conducted at 25±0.25°C.

The experiments conducted during this phase of the project were limited to an investigation of the transient response of cultures metabolizing the composite waste described in Secton V. The reason for limiting the investigation was the difficulty experienced in maintaining an activated sludge culture which had good settling properties. This problem initially manifested itself when batch units, which had been acclimated to the waste and operated to establish a steady state mixed liquor suspended solids concentration, were transfered to the continuous flow system. During the first several days of continuous flow operation, the culture would function with good solids separation in the sedimentation basin. However, invariably there would be an increase in filamentous growth which eventually resulted in partial washout of the culture because of sludge bulking. This problem was alleviated by increasing the concentration of mixed liquor suspended solids (MLSS) in the batch units so the concentration of the chemical oxygen demand (COD) in the influent of the continuous flow system was initially less than 1.5 pounds of COD per day per pound of MLSS. However, sludge bulking still occured occasionally following step increases in the 3-hour mean residence time transient experiments. All of these experiments were therefore conducted with a new culture which was developed form domestic sewage in a batch unit. These units contained 8 liters and were operated on a cycle of 23 hours of aeration followed by 1 hour of settling. Six liters of the supernatant were then withdrawn and replaced by a solution of the composite waste containing 500 mg/L as COD. This procedure was followed for 7 days before transfering the contents of the unit to the continuous flow reactor. The continuous flow system was then operated without sludge wasting for approximately 4 days. Sludge then was wasted at 8-hour intervals to maintain a constant MLSS concentration for 24 to 48 hours before the start of an experiment.

It was not necessary to develop a new culture each time the 6-hour mean residence time experiments were conducted.

Three-Hour Mean Residence Time Experiments

Six step transient experiments were conducted at the 3-hour mean residence time. The combinations studied are summarized in Table 24.

Table 24. Summary of 3-Hour Mean Residence Time Transients Conducted on the Aeration With Sludge Return System.

Influent Concentration COD mg/L	Suspended Solids Concentration Before Starting Transient mg/L
130 - 268	1760
135 - 508	1776
135 - 972	3320
286 - 560	1572
286 - 600	2152
280 - 1104	3716

An example of the parameter response observed during a transition is given in Figure 28. The suspended solids and soluble chemical oxygen demand (COD) values in Figure 28 were observed in the effluent of the aeration basin. The oxygen uptake observations also include only the respiration occuring in the aeration basin.

Figure 28 illustrates a severe case of culture washout beginning approximately 6 hours after the start of the transient. The loss in suspended solids did not effect removal of soluble COD by the culture but did cause a decrease in the oxygen utilization rate. A slight deterioration in settling also occured approximately 6 hours after starting the 130 to 268 mg/L COD transient. In this instance the decrease in suspended solids was not large enough to significantly

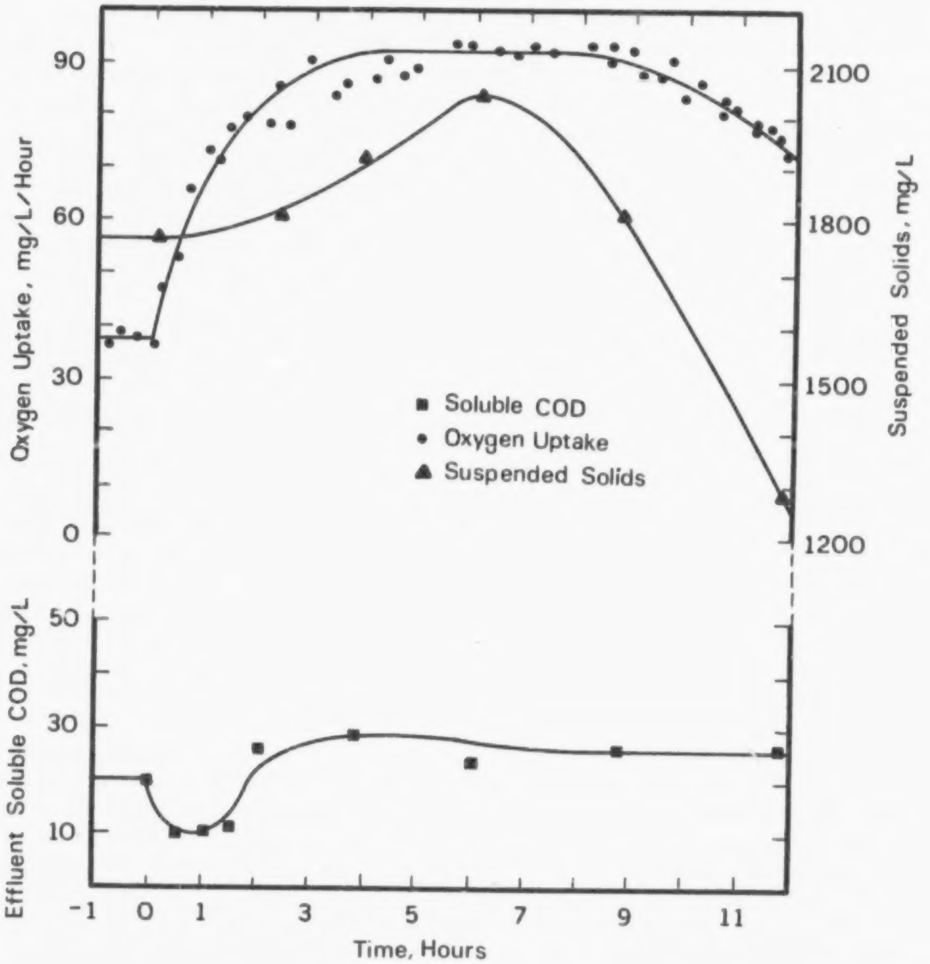

Figure 28. Parameter Response for a Transition from 135 to 508 mg/L Influent COD, Composite Waste, 3-Hour Mean Residence Time, Aeration with Sludge Return

affect the rates of oxygen utilization. Deterioration in settling characteristics was not observed during any of the other transients included in Table 24, but an increase in the concentration of filamentous growth was observed in all except the 135 to 972 and the 280 to 1104 mg/L transients.

Summaries of the oxygen uptake and the soluble COD concentrations observed during the 3-hour mean residence time experiments are given in Figure 29 and Figure 30. The abrupt decrease in the soluble COD observed immediately after the start of a transient was not anticipated because Engelbrecht and McKinney (36) have demonstrated glucose, glutamic acid, and acetate are not readily removed by biosorption and virtually all of the mathematical models of the activated sludge process predict an increase in the soluble COD following a step increase in the influent. A possible explanation may be the polysaccharide slime layer secreted by bacteria during the declining growth phase. A portion of this slime layer may be removed from the bacterial cells by shearing action caused by hydraulic turbulence and subsequently measured as a component of the soluble COD from the aeration basin. When the culture was subjected to an increase in substrate there was an immediate increase in the synthesis of young cells which did not produce the polysaccharide slime layer. The concentration of soluble COD therefore decreased until a balance between synthesis and endogenous respiration was reestablished and the polysaccharide layer was again being sheared from the old cells. This decrease in soluble COD was not observed in the aeration only system because the concentration of biological solids, and therefore, the possible change in polysaccharide concentration, was much smaller. More research in this area is warranted.

The oxygen limitation in the 280 to 1104 mg/L COD transient was caused by the rate of oxygen demand of the culture exceeding the oxygen supply capacity of the respirometer. The dissolved oxygen concentration in the aeration basin was less than 1 mg/L two hours after the start of the transient and remained at this concentration for 10 hours. During this period the concentration of soluble COD in the effluent did not increase. However, the culture would probably have eventually failed due to a shift in predomination toward filamentous organisms.

The oxygen uptake and suspended solids observations for the 3-hour mean residence time aeration with sludge return experiments are summarized in Table 25. No suspended solids were wasted from the system after the start of a transient. the values given in Table 25 for this parameter are therefore indicative of both growth in the culture and the partition of solids between the aeration and the sedimentation basin.

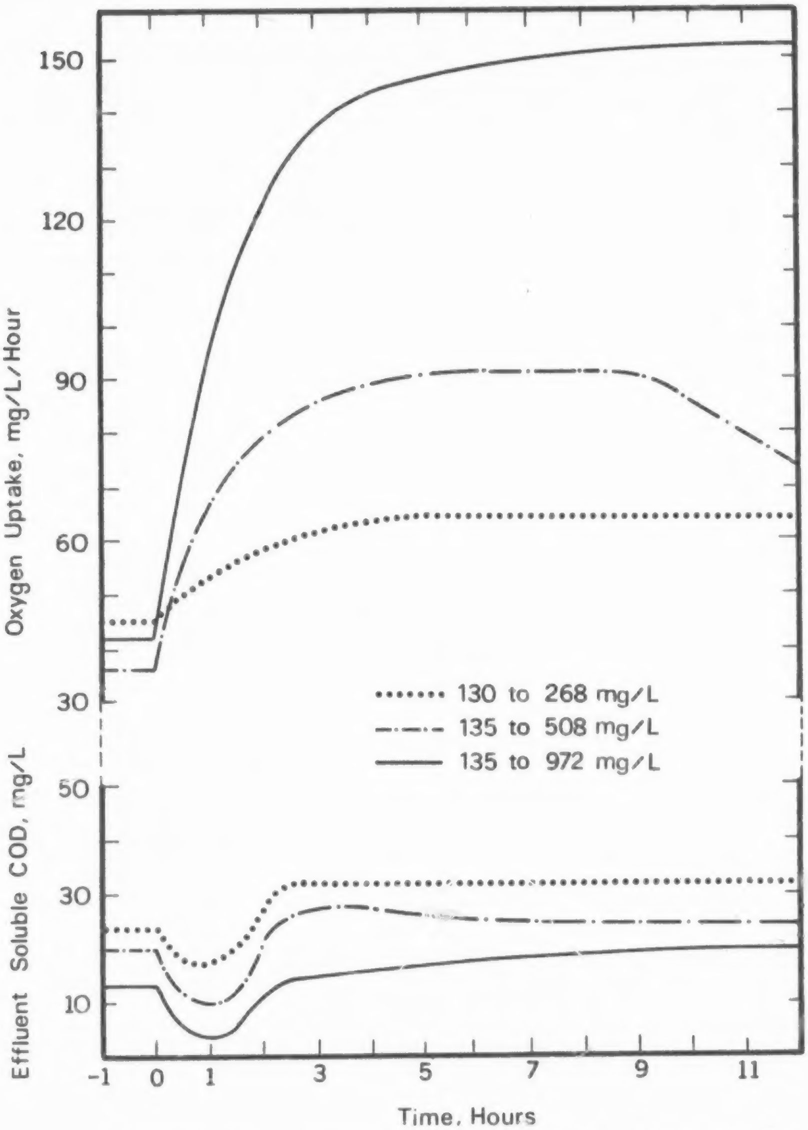

Figure 29. Partial Summary of Changes in Oxygen Uptake Rate and Effluent Soluble COD in Response to Step Increases in the Influent, Composite Waste, 3-Hour Mean Residence Time, Aeration with Sludge Return

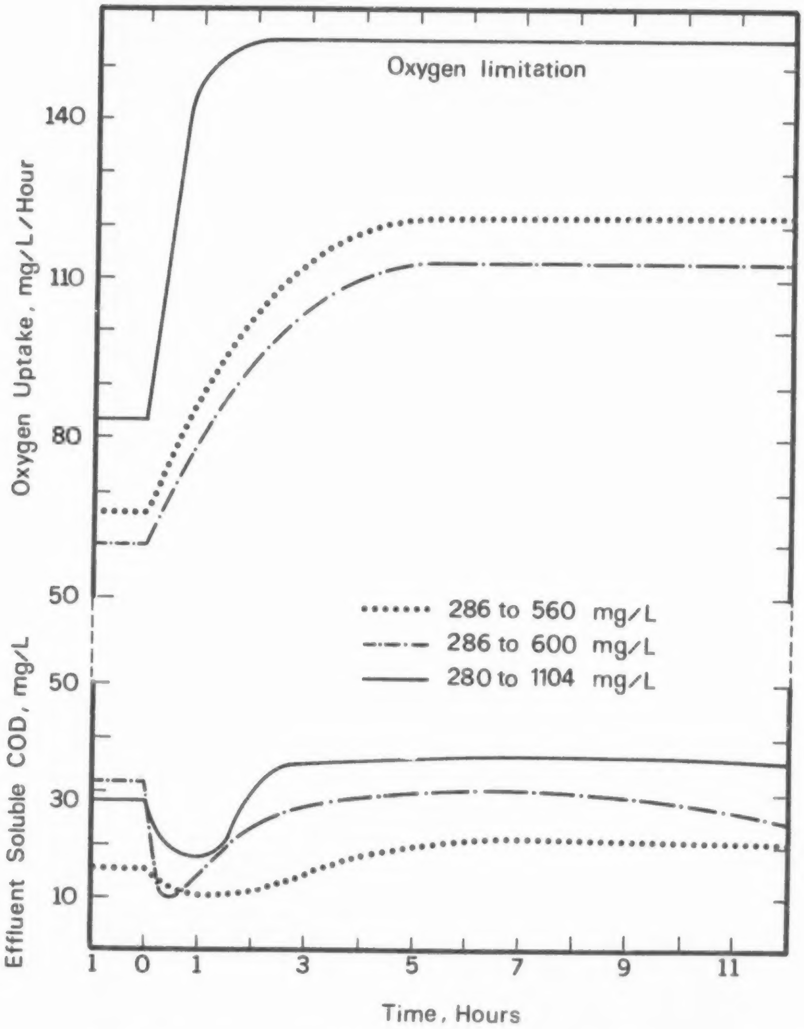

Figure 30. Partial Summary of Changes in Oxygen Uptake Rate and Effluent Soluble COD in Response to Step Increases in the Influent, Composite Waste, 3-Hour Mean Residence Time, Aeration with Sludge Return

Table 25. Summary of Oxygen Uptake Rate and Suspended Solids Concentrations for the 3-Hour Mean Residence Time Aeration With Sludge Return Experiments

Influent COD mg/L	Parameter*	Elapsed Time from Start of Transient, Hours					
		0	1	2	3	6	9
130 to 268	dO_2/dt	47	62	61	67	67	63
	SS	1760	1709**	1658	1720	1806	1850**
135 to 508	dO_2/dt	38	74	78	86	93	92
	SS	1776	1792**	1808	1860**	2028	1810
135 to 972	dO_2/dt	42	94	130	140	148	153
	SS	3320	3412**	3504	3650**	3964	4324
286 to 560	dO_2/dt	67	93	95	107	121	121
	SS	1572	1624**	1676	1750**	1916	2100
286 to 600	dO_2/dt	63	79	91	94	114	113
	SS	2152	2204**	2256	2280**	2430**	2610**
280 to 1104	dO_2/dt	87	154	156	155	-	-
	SS	3716	3796**	3876	4250**	4700**	4628

*dO_2/dt = mg/L/hr SS = mg/L

**Values interpolated from graphical analysis of observations

It was not possible to predict the steady state suspended solids concentrations and cultures with the equations developed by McKinney (24) because the procedure used in developing the stock culture did not establish a steady state sludge age (t_s).

Six-Hour Mean Residence Time Experiments

Four step transients experiments were conducted at the 6-hour mean residence time. The combinations studied are summarized in Table 26.

Table 26. Summary of 6-Hour Mean Residence Time Transients Conducted on the Aeration With Sludge Return System

Influent Concentration COD mg/L	Suspended Solids Concentration Before Starting Transient mg/L
250 - 491	1428
269 - 773	1228
269 -1035	1502
285 -1060	1341

An example of the parameter response observed during a transition is given in Figure 31. The shape of the oxygen uptake curve is very similar to that illustrated in Figure 28 for the 3-hour mean residence time system. The concentration of suspended solids in the aeration basin continued to increase throughout the duration of the transient. This was repeated in three of the four 6-hour mean residence time transients. The sludge remained free from filamentous growth throughout the duration of all of the transients and no change was observed in settling properties.

A partial summary of the oxygen uptake and the soluble COD concentrations observed during the 6-hour mean residence time experiment is given in Figure 32. The data for the 285 to 1060 mg/L COD transient has been omitted from the figure because it is essentially identical to that observed during the 269 to 1035 mg/L COD transient. The abrupt decrease in soluble COD observed in the 3-hour mean residence time ex-

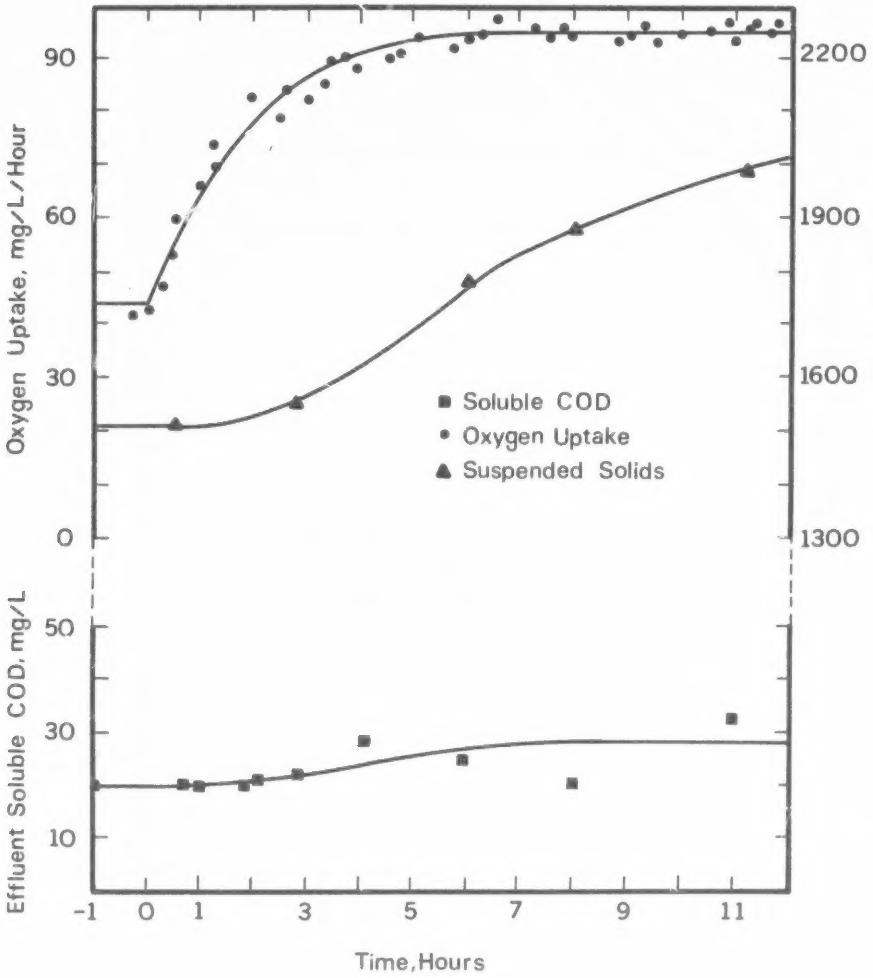

Figure 31. Parameter Response for a Transition from 269 to 1035 mg/L Influent COD, Composite Waste, 6-Hour Mean Residence Time, Aeration with Sludge Return System

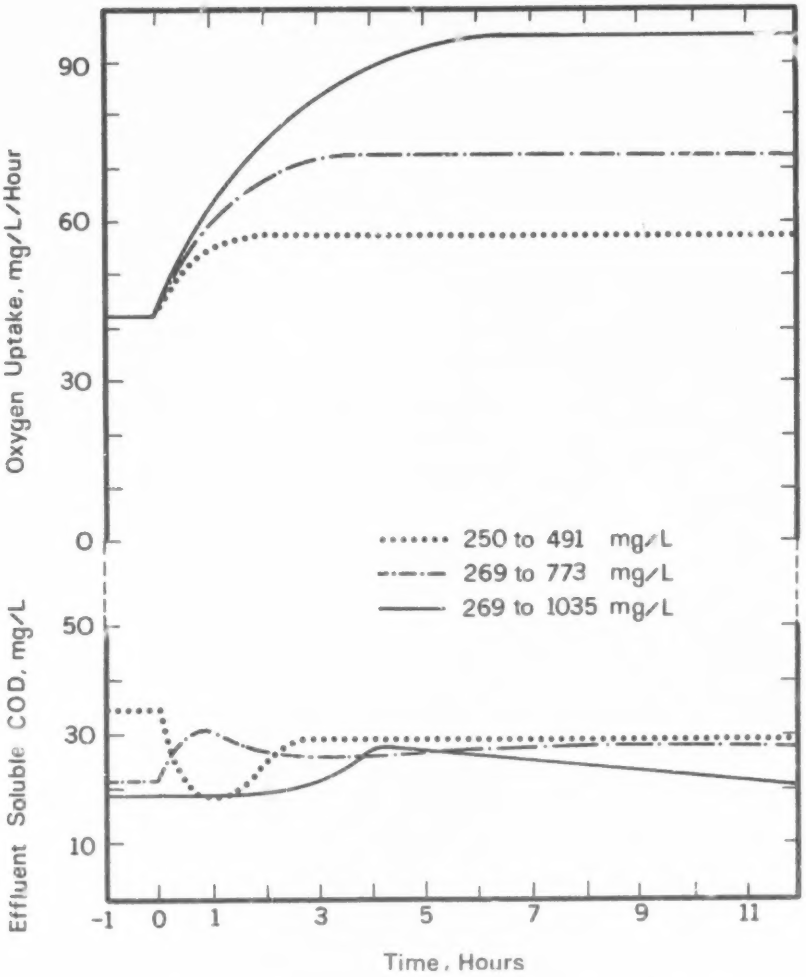

Figure 32. Partial Summary of Changes in Oxygen Uptake Rate and Effluent Soluble COD in Response to Step Increases in the Influent, Composite Waste, 6-Hour Mean Residence Time, Aeration with Sludge Return

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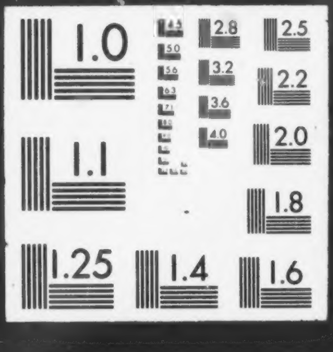
1.0
4.5
5.0
5.6
6.3
7.1
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

periments was observed in only the 2-fold step increase at the 6-hour mean residence time. Both of the other transients showed slight increases. If the hypothesis advanced earlier concerning the polysaccharide slime layer is correct, there was apparently enough unmetabolized influent passing through the system during the larger step transients to mask the interaction between growth state and hydraulic turbulence. The increase in soluble COD was not large enough in either transient to be significant in a practical sense.

The oxygen uptake and suspended solids observations for the 6-hour mean residence time aeration with sludge return experiments are summarized in Table 27. No suspended solids were wasted from the system after the start of a transient.

It was not possible to predict the steady state suspended solids concentrations and oxygen uptake rates of the culture with the equations developed by McKinney (24) because the adjustment period between experiments was not long enough to establish a steady state sludge age (t_s).

Discussion

Difficulties with filamentous growth in activated sludge systems is not new. Carter (44) has presented an extensive literature review on sludge bulking especially as it applies to substrates containing glucose. The most common causes of filamentous growth have been low concentrations of dissolved oxygen, nitrogen and iron deficiencies, and high loading rates in the influent waste.

In this research, dissolved oxygen levels in excess of a 2 mg/L and an excess of nitrogen, iron, and other nutrients were maintained. The key parameter in the development of filamentous growth therefore appeared to be the loading rate. The loading rates used are summarized in Table 28.

In the 3-hour mean residence time experiments, the units having a steady state loading rate less than 0.7 pounds of COD per day per pound of MLSS had a well balanced biological population with no filamentous growth. The two experiments which had a steady state loading rate greater than 1 pound of COD per pound of MLSS had a limited amount of filamentous growth. All of the experiments, except the 135 to 972 and the 280 to 1104 mg/L influent COD, developed filamentous growth after the start of the transient. The two transients which did not develop filamentous growth had a MLSS concentration greater than 3000 mg/L.

Table 27. Summary of Oxygen Uptake Rates and Suspended Solids Concentrations for the 6-Hour Mean Residence Time Aeration With Sludge Return Experiments

Influent COD mg/L	Parameter*	Elapsed Time from Start of Transient, Hours					
		0	2	4	6	9	12
250 to 491	dO_2/dt	42	56	59	58	59	56
	SS	1428	1436	1470**	1460**	1424	1250**
269 to 773	dO_2/dt	41	67	72	71	73	75
	SS	1229	1290**	1450	1482	1630**	1800**
269 to 1035	dO_2/dt	44	79	88	94	95	97
	SS	1502	1530**	1830	1776	1930**	2000**
285 to 1060	dO_2/dt	40	81	89	88	94	96
	SS	1341	1500**	1525**	1610**	1790**	1842

*dO_2/dt = mg/L/hr SS = mg/L

**Values interpolated from graphical analysis of observations

Table 28. Organic Loading Rates Imposed on the Continuous Flow Aeration with Sludge Return Activated Sludge Systems

Influent Concentration COD mg/L	Steady State Loading Rate lb COD/day/lb MLSS	Initial Transient Loading Rate lb COD/day/lb MLSS
3-Hour Mean Residence Time		
130 to 268	0.63	1.30
135 to 508	0.60	2.26
135 to 972	0.33	2.36
286 to 560	1.46	2.85
286 to 600	1.06	2.23
280 to 1104	0.61	2.40
6-Hour Mean Residence Time		
250 to 491	0.70	1.38
269 to 773	0.88	2.53
269 to 1035	0.72	2.76
285 to 1060	0.85	3.16

No filamentous growth was observed during the 6-hour mean residence time experiments either before or after the start of a transient.

These findings partially confirm the report of Adams and Eckenfelder (45) regarding the growth of filamentous organisms, during transient conditions. However, this research strongly indicates loading rate by itself does not define the conditions which produce filamentous growth. The concentration of suspended solids and the hydraulic mean residence time in the aeration basin are also significant factors.

Additional studies should be undertaken to more fully define this interrelationship.

SECTION VIII
ENGINEERING SIGNIFICANCE

Oxygen Requirements During Transient Conditions

This research has demonstrated both aeration only and aeration with sludge return activated sludge systems are capable of responding to step increases in the influent substrate without an increase in the concentration of COD in the effluent. A satisfactory method of estimating the oxygen uptake rate at any time during this type of transient can be developed by considering the fundamental microbiology of the system.

At steady-state the total rate of oxygen demand by a culture is the sum of the oxygen used in synthesis reactions, the oxygen used for endogenous respiration, and the oxygen used for nitrification. The oxygen demand exerted by the synthesis reactions is directly dependent on the rate biodegradable organic material is added to the aeration basin. The oxygen used for endogenous respiration is dependent upon the cell mass. The oxygen used for nitrification is dependent upon the concentration of oxidizable nitrogen and the presence of nitrifying bacteria.

During transient conditions the oxygen demand exerted by synthesis reactions increases rapidly. The increase in oxygen demand by endogenous respiration and nitrification is related to the increase in active cell mass in the system and is therefore relatively slow. This interrelationship is illustrated in Figure 33. In this figure the oxygen demand rate by endogenous respiration and nitrogenous oxidation is designated as the basal rate. The oxygen uptake rate at any time during a transient (t_t) is equal to the sum of:

A. the demand rate due to synthesis of the influent biodegradable organic load at time (t_t),
B. The basal rate during steady-state operation, and
C. the increase in basal rate due to the buildup of cell mass from the start of the transient until time (t_t).

Only after the cell mass has attained a new equilibrium will a true steady state oxygen uptake rate be reestablished. In an aeration only system this will take place within 3 mean residence times. However, the basal rate is only a small fraction of the total oxygen used in an aeration only system so the new steady state oxygen uptake is essentially established in one mean residence time.

The magnitude of the steady-state basal oxygen uptake rate and the increase in this rate during a transient are much more significant in an aeration with sludge return activated sludge system because the biological solids are continuously being recycled to the aeration basin instead of being discharged in the effluent. This results in a more rapid increase in the MLSS in the aeration basin during a transient.

An estimate of the rate of oxygen uptake at any time (t_t) during a transient can be obtained by two steps. The first is to examine the steady-state conditions preceding the transient by the following technique:

(a) Compute the oxygen uptake under steady-state conditions using the equations developed by McKinney (24). This value is designated as $dO/dt_{(s)}$. If accurate experimental measurements of the steady-state oxygen demand are available these may be used in lieu of the computed value.

(b) Compute the steady-state oxygen demand rate due to synthesis. This value, designated O_{ss}, is obtained by:

$$(18) \quad O_{ss} = 0.33 \left(\frac{BOD_u}{t}\right)$$

where O_{ss} = steady-state oxygen uptake rate due to synthesis, mg/L/Hr.

t = mean residence time in the aeration basin, hours

BOD_u = ultimate biochemical oxygen demand of the influent, mg/L

The constant 0.33 in equation 18 is based on an energy-synthesis relationship of 1/3 - 2/3. This value has been obtained on domestic wastes by McKinney (23). Burkhead (33) has also obtained this value for the composite waste used in this research.

(c) Compute the steady-state basal rate. This value, designated O_{bs}, is obtained by:

$$(19) \quad O_{bs} = \frac{dO}{dt_{(s)}} - O_{ss}$$

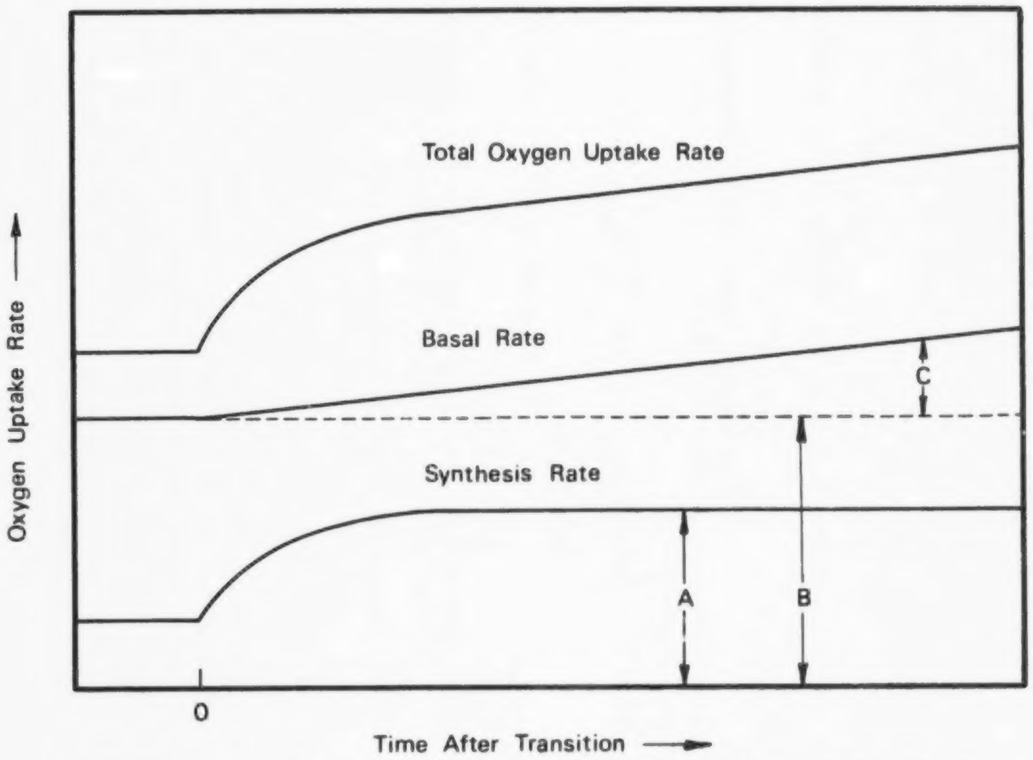
Total Oxygen Uptake Rate
Basal Rate
Synthesis Rate
C
A
B
0
Oxygen Uptake Rate
Time After Transition

Figure 33. Relationship Between Synthesis and Basal Oxygen Uptake Rate During a Step Transient

where O_{bs} = steady-state basal oxygen uptake rate

$\frac{dO}{dt(s)}$ = total oxygen uptake rate at steady-state

The second step is to determine the change in synthesis and endogenous respiration that occurs during the transient. If we assume the concentration of unmetabolized substrate leaving the reactor is negligible, the magnitude of the synthesis reaction is equal to the new steady-state after one hydraulic mean residence time has elapsed. The increase in synthesis is approximately 87 percent at the end of the first one third and 98 percent at the end of the second one third of the first hydraulic mean residence time. The oxygen uptake due to synthesis during a transient is:

$$(20)\quad O_{st} = 0.33 \left(\frac{BOD_u}{t}\right)\left(1 - e^{-2t_t}\right)$$

for the 3 hour mean residence time and by:

$$(21)\quad O_{st} = 0.33 \left(\frac{BOD_u}{t}\right)\left(1 - e^{-t_t}\right)$$

for the 6 hour mean residence time.

where O_{st} = oxygen uptake rate due to synthesis during a step transient, mg/L/hr.

t_t = elapsed time since start of the transient, hours.

The increase in endogenous respiration is obtained by assuming all the protoplasm synthesized during the transient remains in the aeration basin. This is not true because some of the material leaves in the effluent. However, during the first hydraulic mean residence time after the start of the transient the magnitude of the error introduced by this assumption is very small. This is especially true in the aeration with sludge return system. The increase in oxygen uptake by endogenous respiration is given by:

$$(22)\quad O_{bt} = 0.47Ket_t\left(\frac{BOD_u}{t}\right)$$

where Ke = endogenous respiration constant as defined by McKinney (24)

The constant 0.47 in equation 22 is based on the energy-synthesis relationship cited in equation 18 and a factor to convert activated sludge mass units to oxygen equivalents.

The total oxygen demand rate at any time during a step transient is therefore:

$$(23)\quad \frac{dO}{dt}_{(t)} = O_{bs} + O_{st} + O_{bt}$$

where $\frac{dO}{dt}_{(t)}$ = total oxygen uptake rate at any time during a step transient, mg/L/hr.

To illustrate this procedure, example calculations using the data from the 135 to 508 mg/L influent COD transient illustrated in Figure 28 are given below. The steady-state oxygen uptake rate for this 3-hour mean residence time system was 38 mg/L/hr. If we assume the influent COD is equal to the ultimate BOD of the composite waste, the predicted oxygen uptake 2 hours after the start of the transient is:

$$O_{ss} = 0.33\ (\frac{135}{3}) = 15 \text{ mg/L/hr}$$

$$O_{bs} = 38 - 15 = 23 \text{ mg/L/hr}$$

$$O_{st} = 0.33(\frac{508}{3})(1-e^{-4}) = 55 \text{ mg/L/hr}$$

$$O_{bt} = (0.47)(0.028)(508)(\frac{2}{3}) = 4 \text{ mg/L/hr}$$

$$\frac{dO}{dt}_{(t)} = 23 + 55 + 4 = 82 \text{ mg/L/hr}$$

The observed oxygen uptake rate was 78 mg/L/hr.

The observed and predicted transient oxygen uptake rates for both the aeration only and the aeration with sludge return transients conducted with the composite waste are given in Table 29 and Table 30. Good agreement between the predicted and the observed values was obtained for both the 3 and the 6-hour mean residence time systems during the first 6 hours of a transient. After this interval the predicted values are consistently high. This illustrates an accumulative departure from the assumption that all of the biological solids synthesized during the transient remain in the

Table 29. Summary of Observed and Predicted Oxygen Uptake Rates for the 6-Hour Mean Residence Time System, Composite Waste

Influent COD mg/L	Oxygen Uptake Rate mg/L/Hr	Elapsed Time from Start of Transient, Hours				
		2	4	6	9	12
250 to 491	Observed Predicted	56 53	59 58	58 60	59 63	56 66
269 to 773	Observed Predicted	67 66	72 75	71 78	73 83	75 88
269 to 1035	Observed Predicted	79 84	88 95	94 100	95 107	97 114
285 to 1060	Observed Predicted	81 80	89 90	88 96	94 103	96 110
250 to 504*	Observed Predicted	33 30	37 35	35 39	37 42	36 52
235 to 736*	Observed Predicted	39 44	50 52	51 56	47 61	54 66

*Aeration Only all other transients are Aeration with Sludge Return

Table 30. Summary of Observed and Predicted Oxygen Uptake Rates for the 3-Hour Mean Residence Time System, Composite Waste

Influent COD mg/L	Oxygen Uptake Rate mg/L/Hr	Elapsed Time from Start of Transient, Hours				
		1	2	3	6	9
130 to 268	Observed	62	61	67	67	63
	Predicted	60	64	66	69	73
135 to 508	Observed	74	78	86	93	92
	Predicted	74	82	86	93	100
135 to 972	Observed	94	130	140	148	153
	Predicted	124	141	147	160	170
286 to 560	Observed	93	95	107	121	121
	Predicted	92	101	105	112	119
286 to 600	Observed	79	91	94	114	113
	Predicted	92	102	106	114	122
478 to 717*	Observed	84	90	89	91	90
	Predicted	81	92	97	106	115
214 to 411*	Observed	41	46	50	55	54
	Predicted	45	52	54	59	64

*Aeration Only all other transients are Aeration with Sludge Return aeration basin.

In the aeration only system the predicted oxygen uptake rate after one mean residence time can be safely used for determining the maximum demand on the oxygen transfer system. The maximum rate of oxygen uptake observed in solids return units will, in part, be dependent on the efficiency of the solids separation and recycle system. On the basis of this research, the oxygen uptake rate conputed for periods up to 6 hours after the start of a transient can be safely used for design purposes.

Selection of an oxygen demand rate for design of a treatment plant should be based on a thorough knowledge of the magnitude and frequency of the transient loading conditions which are expected to occur. If transient conditions are infrequent and less than one hour in duration, the average loading rate on the system can be used to determine the oxygen demand rate for design purposes. In aeration with sludge return systems this rule holds even if the transient load is very large because these units can operate under oxygen limiting conditions for short periods without deterioration of the effluent. In aeration only systems this rule holds from the standpoint of the oxygen supply system but a transient deterioration in effluent quality may occur.

If the treatment system is to be subjected to frequent, high magnitude, long duration transients, oxygen transfer capacity in excess of the average demand rate must be provided. Under these conditions, substituting the maximum loading rate into steady state equations, such as those developed by McKinney (24), will result in predictions which are significantly higher than what is actually observed in sludge recycle systems because the sludge mass is not in equilibrium. In aeration only systems treating soluble wastes, the opposite condition occurs because the culture may shift into exponential growth and produce an oxygen uptake peak significantly greater than the steady-state value.

The results of this research provide guidlines which can be used by the design engineer to size the oxygen transfer facilities in both instances.

Aeration Only Activated Sludge Systems

The 3-hour mean residence time aeration only systems were capable of withstanding a 2-fold increase in the influent without an increase in the soluble COD in the effluent. The capability to resist a shock load without deterioration of the effluent was increased to 3-fold in the 6-hour mean residence time systems. This research was conducted at 25°C and the ability to successfully respond to a shock load is directly related to the rate of metabolism in the culture. Therefore, the maximum permissible transient at 15°C can be expected to be about one half the values given above. In most applications, temperatures of 15°C or lower can be expected during part of each year. If this occurs, short term aeration only systems, similar to those suggested by Tenney *et al* (5)(6), will be restricted in their usefulness. Under these conditions a second treatment process will be required to reduce the concentration of the soluble COD in the effluent to acceptable levels.

Aeration With Sludge Return Activated Sludge Systems

This research has again demonstrated that completely mixed activated sludge (CMAS) systems with solids recycle can handle large step increases in soluble organic loading without an increase in soluble COD in the effluent. Step increases of up to 7.2 times did not produce a change in the effluent soluble COD. This was not the maximum limit, however, because the system was not loaded to failure.

One of the keys to successful operation of any CMAS system is the capability of separating the microbial solids in the secondary sedimentation basin. Loading rate was found to be a critical factor in the production of filamentous growth in systems metabolizing substrates containing glucose.

However, sludge bulking was prevented by maintaining the MLSS concentration in the aeration basin between 3000 to 4000 mg/L. Additional research in this area is warranted.

SECTION IX
ACKNOWLEDGEMENTS

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SECTION XI
PUBLICATIONS AND PATENTS

The following publications have been produced during the course of this project:

Agnew, R.W., "The Oxygen Uptake of a Biological Culture Subjected to Transient Organic Loadings", Ph.D. Dissertation, Univ. of Kansas, Lawrence, Kansas (1968). Available from, University Microfilms, Dissertation Copies, P.O. Box 1764, Ann Arbor, Michigan, 48106.

Chun, M.J., "Oxygen Response of a High Solids Completely Mixed Activated Sludge System to Transient Loadings" Ph.D. Dissertation, Univ. of Kansas, Lawrence, Kansas (1970). Available from University Microfilms at above address.

Agnew, R.W., and O'Brien, W.J., "The Oxygen Uptake Response of an Activated Sludge System to Changes in Influent Substrate Concentration", Presented at the 42nd Annual Conference, Water Pollution Control Federation, Dallas, Texas (1969).

O'Brien, W.J., Agnew, R.W., and Chun, M.R., "A Continuous Flow Automatically Recording Respirometer", accepted for publication in Biotechnology and Bioengineering.

No patents have been applied for in connection with this research.

SECTION XII
GLOSSARY

A - The oxygen uptake rate due to synthesis of the influent biodegradable organic load at time (t_t).

Actinomycete - A large and distinctive group of eubacteria. The actinomycetes are coenocytic organisms with a characteristic mycelial vegetative structure, analogous to that which exists in higher fungi.

Activated Sludge Process - A biological wastewater treatment process in which a mixture of wastewater and activated sludge is agitated and aerated. The activated sludge is subsequently separated from the treated wastewater (mixed liquor) by sedimentation and wasted or returned to the process as needed.

Aeration Only Activated Sludge Process - A single pass activated sludge process without sedimentation and sludge return. All of the activated sludge is wasted with the effluent of the aeration tank.

Aerobic - Requiring, or not destroyed by, the presence of free elemental oxygen.

Anaerobis - The absence of air or free (elemental) oxygen.

B - Correction for change in barometric pressure, mg/min or the basal oxygen uptake rate during steady state operation.

Bacteria - A group of universally distributed, rigid, essentially unicellular microscopic organisms lacking chlorophyll. Bacteria usually appear as spheroid, rod-like, or curved entities, but occasionally appear as sheets, chains, or branched filaments. Bacteria are usually regarded as plants.

Basal Rate - The oxygen demand rate created by endogenous respiration and nitrogenous oxidation.

Biochemical Oxygen Demand (BOD_5)- The quantity of oxygen used in the biochemical oxidation of organic matter in a specified time, at a specified temperature, and under specified conditions. A standard test used in assessing wastewater strength.

Biodegradable - The character of a substance which allows its destruction or metabolism by microorganisms populating soils, natural bodies of water, or wastewater treatment systems.

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$\underline{BOD_u}$ - Ultimate biochemical oxygen demand of the influent, mg/L.

Bulking Sludge - An activated sludge that settles poorly because of a floc of low density.

C - The increase in basal rate due to the buildup of cell mass from the start of the transient until time (t_t).

Cell Yield - Refers to the production of microbial solids from a given food source under controlled environmental conditions.

Chelation - The formation of an inner complex compound soluble in water in which the same molecule is attached to a central atom at two different points, forming a ring structure.

Chemical Oxygen Demand (COD) - A measure of the oxygen-consuming capacity of inorganic and organic matter present in water or wastewater. It is expressed as the amount of oxygen consumed from a chemical oxidant in a specific test. It does not differentiate between stable and unstable organic matter and does not necessarily correlate with biochemical oxygen demand. Also known as OC and DOC, oxygen consumed and dichromate oxygen consumed, respectively.

Declining Growth - The condition of biological growth where the food supply is inadequate to meet the demands of the microbial population. Also called a food limiting condition.

Detention Time - The theoretical time required to displace the contents of a tank or unit at a given rate of discharge (volume divided by rate of discharge).

Dilution Rate (D)- The influent flow rate into a reactor which results in the dilution and washout of the reactor contents.

Discrete Particles - Nonflocculant particles which remain discrete in a settling process, i.e., they will not agglomerate or flocculate into larger particles but remain as individual particles during their subsidence in a quisicent condition.

Dissolved Oxygen (DO) - The oxygen dissolved in water, wastewater, or other liquid, usually expressed in milligrams per liter, parts per million, or percent of saturation. Abbreviated DO.

$\frac{dO}{dt} = \frac{dO_2}{dt}$ - Oxygen utilization rate, mg/L/hr.

$\frac{dO}{dt}_{(s)}$ - Total oxygen uptake rate at steady state, mg/L/hr.

$\frac{dO}{dt}_{(t)}$ - Total oxygen uptake rate at any time during a step transient, mg/L/hr.

Effluent BOD_5 - Five day biochemical oxygen demand of the effluent.

Endogenous Respiration - The oxygen utilization process of microorganisms caused by the oxidation of endogenous or previously accumulated substances within the cells.

Equilibrium - A condition which exists within a biological reactor where a process parameter remains constant with time.

Error - A measure of the accuracy or the difference between a measured value and the true value in question. It is often expressed as a percentage.

Filamentous Growth - Characterized by threadlike structures.

Filtrability - The ease or difficulty of solids separation of a solid-liquid mixture by filtration.

Flocculation - In water and wastewater treatment, the agglomeration of colloidal and finely divided suspended matter after coagulation by gentle stirring by either mechanical or hydraulic means. In biological wastewater treatment where coagulation is not used, agglomeration may be accomplished biologically.

Food Limiting - See Declining Growth conditions.

F - Concentration of BOD_5 in the effluent, mg/L.

F_i - Concentration of BOD_5 in raw waste, mg/L.

$\frac{dF}{dt}$ - Food utilization rate, mg/L/hr.

Fungi - Small non-chlorophyll-bearing plants which lack roots, stems or leaves, which occur (among other places) in water, wastewater, or wastewater effluents and grow best in the absence of light. Their decomposition after death may cause disagreeable tastes and odors in water; in some wastewater treatment processes they are helpful and in others they are detrimental.

Hydraulic Displacement or Washout - The physical removal of liquid from a biological reactor by the displacement of the reactor contents with the incoming wastewater flow.

Inhibitory - A stopping or slowing down of a biological process by the introduction and/or buildup of process retarding substances antagonistic to the microorganisms.

K_b - BOD_5 factor for converting active mass to oxygen equivalent (not temperature dependent because the BOD_5 test is performed at 20°C).

K_e - Endogenous respiration constant (temperature dependent).

K_m - Metabolism constant (temperature dependent).

K_s - Synthesis constant (temperature dependent) or substrate concentration when the specific growth rate is one half the maximum specific growth rate.

Load, Loading Condition, Loading Rate - The application of liquid or contaminants to a wastewater treatment system or to a body of water in terms of gallons or pounds, respectively, per unit volume or mass of the reactor per unit time.

Ma - Active microbial mass, mg/L

Ma_r - Active microbial mass in the return sludge, mg/L.

$\frac{dMa}{dt}$ - Rate of change in active mass,mg/L/hr.

Me - Endogenous respiration mass, mg/L.

Mean Residence Time - The average time that liquid is detained in a biological reactor as determined by the quotient of the reactor volume by the influent flow rate.

Metabolism - The process in which food is utilized and wastes formed by living matter.

M_I - Inert, non-biodegradable organic suspended solids in the aeration tank, mg/L VSS.

$M_{I_{inf}}$ - Inert, non-biodegradable organic solids in influent, mg/L VSS

M_{II} - Inert, inorganic suspended solids in the aeration tank, mg/L SS.

$M_{II_{inf}}$ - Inert, inorganic suspended solids in influent, ash fraction of influent suspended solids, mg/L SS.

MLSS - Mixed liquor suspended solids, mg/L.

MLVSS - Mixed liquor volatile suspended solids, mg/L.

M_T - Same as MLSS

Nitrification - An aerobic biological process where ammonia is oxidized to nitrites and nitrates.

Non-biodegradable - The character of a substance which make it resistant to biological degradation.

Nutrient - A food source for microorganisms.

$O_2(E)$ - Oxygen supplied by electrolysis.

$O_2(net)$ - Oxygen used by the culture, mg/min.

O_{bs} - Steady state basal oxygen uptake rate, mg/L/hr.

O_{bt} - Increase in basal oxygen uptake rate during a step transient, mg/L/hr.

O_{ss} - Steady state oxygen uptake rate due to synthesis, mg/L/hr.

O_{st} - Oxygen uptake rate due to synthesis during a step transient, mg/L/hr.

Oxygen Equivalents - The amount of elemental oxygen theoretically required to oxidize a given amount of organic material to carbon dioxide and water.

Oxygen Limitation, Oxygen Limiting - Condition of a microbial culture where the dissolved oxygen concentration is the limiting factor in the metabolic process.

Oxygen Uptake, Oxygen Uptake Rate See $\frac{dO}{dt}$

P - Oxygen demand constant.

Polyelectrolyte - Complex organic polymer containing ionizable groups. Use in the wastewater field for the removal of colloidal and particulate contaminants.

Protoplasm - The substance of all living cells.

Protozoa - Small one-celled animals including amoebae, ciliates, and flagellants.

Q - Rate of flow for the raw waste, L/hr.

Q_r - Rate of flow for the return sludge, L/hr.

Respirometer - An instrument used to measure the respiration rate of microorganisms.

S - Substrate concentration in the reactor.

S_o - Influent substrate concentration

Secondary Wastewater Treatment - The treatment of wastewater by biological methods after primary treatment by sedimentation.

Sedimentation - The process of subsidence and deposition of suspended matter carried by water, wastewater, or other liquids, by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. Also called settling.

Shock Loading - The addition of liquid or waste contaminants to a wastewater treatment system in excess or less than that previously added to created an equilibrium condition in the system.

Sludge Wasting - The sludge produced in an activated sludge process that is not needed to maintain the process and therefore not returned to the aeration tank.

Solids Dewatering - The process of removing a part of the water in sludge by any method such as draining, evaporation, pressing, vacuum filtration, centrifuging, exhausting, passing between rollers, acid flotation, or dissolved-air flotation with or without heat. It involves reducing from a liquid to a spadable condition rather than merely changing the density of the liquid (concentration) on the one hand or drying (as in a kiln) on the other.

Solids Recycle - The return of a concentrated activated sludge (usually by secondary sedimentation) to the aeration tank in order to increase the solids concentration in the tank.

SS - Suspended solids, mg/L.

Standard Deviation - A measure of the reproducibility of a test or measurement.

Steady State - See Equilibrium.

Substrate - See Nutrient.

Supernatant - The liquid standing above a sediment or precipitate.

t - Aeration time based on raw waste flow or mean residence time in the aeration basin, hr.

t_s - Sludge turnover time, hr.

t_t - Elapsed time since start of the transient, hr.

T - Temperature.

Total Oxygen Demand (TOD) - The oxygen demand of a wastewater when all of its constituents are completely oxidized.

Toxic - The property of a substance to poison a biological system and inhibit or stop its processes. See Inhibit.

Trace Metals - Metallic elements of dilute concentration necessary to support biological life.

Transient - An unsteady state or nonequilibrium condition where the concentration of a given substance varies with time.

Ultimate BOD - The total biochemical oxygen demand that would be exerted if all of a biodegradable substrate were oxidized to CO_2 and H_2O.

V - Volume of aeration basin, liters, or the liquid volume pumped through reactor, liters/min.

VSS - Volatile suspended solids, mg/L.

Yield Factor (Y) - Dry weight of cells formed per unit weight of substrate utilized.

SECTION XIV
APPENDICES

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A. Bibliography on Theoretical and Applied Research on Activated Sludge and Other Continuous Culture Systems 118

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Appendix A

Bibliography on Theoretical and Applied Research on Activated Sludge and Other Continuous Culture Systems

1. Abu Samra, A. J., "Effect of Substrate Variation in Aeration Only, Complete Mixing, Activated Sludge Systems," Master of Science Thesis, Univ. of Kansas, Lawrence, Kansas (1965).

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